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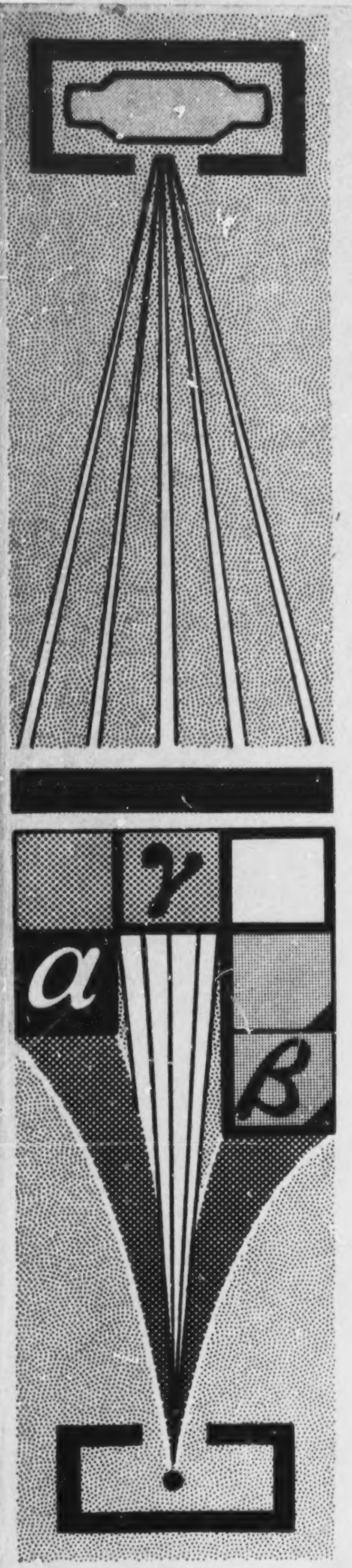

# PARTICLE ACCELERATOR SAFETY MANUAL

CONTRACT PH 86-67-193

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PB 182 335

# PARTICLE ACCELERATOR SAFETY MANUAL

Brobeck (William M.) Associates
Berkeley, California

October 1968

MORP 68-12

# PARTICLE ACCELERATOR SAFETY MANUAL

prepared by
William M. Brobeck and Associates
Berkeley, California

under
Contract PH 86–67–193
for
Radioactive Materials Section
Medical and Occupational Radiation Program

OCTOBER 1968

**U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE**
**Environmental Control Administration**
**National Center for Radiological Health**
**Rockville, Maryland 20852**

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The Center publishes its findings in *Radiological Health Data and Reports* (a monthly publication), the *Environmental Health Series*, Public Health Service numbered reports, appropriate scientific journals, and Program and Branch technical reports.

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I encourage the readers of these reports to inform the Center of any omissions or errors. Your additional comments or requests for further information are also solicited.

James G. Terrill

James G. Terrill, Jr.
Center Director

# PREFACE

The development of this Particle Accelerator Safety Manual was sponsored by U.S. Public Health Service Contract No. PH 86-67-193 with William M. Brobeck and Associates, Berkeley, California.

The National Center for Radiological Health recognizes the lack of knowledge and understanding associated with the use and safe operation of most of the more common accelerators. This Manual was written in an attempt to (1) briefly describe each of the accelerators, (2) provide a review of the more important hazards (with emphasis on the radiation safety hazards), and (3) indicate some of the considerations to be evaluated when reviewing or observing the operation of a particle accelerator facility.

The Manual was prepared under the direction of Mr. William M. Brobeck. Project Officers for the contract were Messrs. Richard F. Boggs and Walter E. Gundaker of the Radioactive Materials Section, Medical and Occupational Radiation Program, National Center for Radiological Health. Many other individuals have contributed to the preparation and review of the material and while it is impossible to enumerate all of those persons, their assistance is sincerely appreciated.

John C Villforth

John C. Villforth
Chief, Medical and Occupational
Radiation Program

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# 1. INTRODUCTION

The number of accelerators in use in medicine, industry, and research is increasing due to the rapid development of new applications for these machines and to their increasing commercial availability. While the special hazard associated with particle accelerators is that of the ionizing radiation which they produce, many of the more common hazards of industrial plants and laboratories are also present. Experience has shown that these conventional hazards are of great importance in accelerator facilities. However, the relative unfamiliarity of certain radiation hazards, and the fact that specialized instrumentation and knowledge are required in order even to recognize that a radiation hazard exists, makes the radiation hazards of particle accelerators qualitatively different from the other hazards. This Manual emphasizes the radiation hazards of particle accelerators. However, material on other recognized hazards is also included.

Safety education and training for personnel who operate and maintain particle accelerators and their associated equipment is imperative. Instruction in the operation of the accelerator itself is not enough. It should be the responsibility of the facility management, through the radiation protection supervisor, to develop and disseminate information on all aspects of safety related to the accelerators installed at the facility. This should include full consideration of mechanical, electrical, toxic chemical, fire and explosion hazards, as well as radiological health hazards.

The purpose of this Manual is to alert the reader to the various hazards and recommend safe practices for common types of accelerators found in the fields of medicine, industry and research. Through the use of this Manual, persons relatively unfamiliar with particle accelerators should be able to identify a specific machine and review the safety considerations of the installation.

Section three of the Manual is devoted to descriptions of accelerators in general - what they are, what they do, and for what they can be used. It also describes the specific types of machines covered by the Manual. The identifying features and the basic operating principles of each machine are given together with schematic diagrams and drawings. These descriptions have been written to aid persons who have a basic understanding of the more detailed descriptions included in the operating manuals and schematic drawings provided by the accelerator manufacturer.

Section four describes the radiation hazards of accelerators in general. Background material is included in this section to permit appreciation of these hazards and to provide a logical basis for the recommendation of safe practices. Section four also describes the instruments used for the detection and measurement of the types of radiation present at accelerator facilities.

The nonradiation hazards of an accelerator facility are covered briefly in section five. The special features of accelerators and their use are related to the more conventional occupational hazards.

In section six, the responsibilities for insuring personnel safety at an accelerator facility are discussed.

References, tables, and examples of calculations are included in the appendix to provide sources of more information for further study where desired.

## 2. SCOPE

The intent of this Manual is to provide safety guidelines for the control of the hazards associated with radiation-producing accelerators. Thus the Manual, being advisory in nature, does not state rules or regulations, but describes the hazards which may exist and how these hazards may be avoided or reduced. Emphasis is on the moderate-energy accelerators which are commercially available and which are currently used in industry, educational institutions, hospitals, and government facilities, engaged in research, radiation therapy, isotope production, radiation processing, and radiography. A discussion of high-energy accelerators with their associated hazards, such as are found in the large national laboratories, are not covered by this Manual, since it was felt that among the personnel of these laboratories experts are available who are cognizant of the complex hazards of their machines and are competent to deal with them.

The particular types of accelerators covered in this Manual are:

Potential-drop Accelerators (Van de Graaff, Cockcroft-Walton, Dynamitron, Resonant Transformer, Insulating-Core Transformer)
Electron Linear Accelerators
Betatrons
Cyclotrons

The common low voltage X-ray machines used for medical and industrial radiography are not included. These machines, their hazards and recommended safe practices, are covered by existing literature.

The reader should refer to and be familiar with State or Federal regulations and standards regarding exposure to ionizing radiation, accelerator shielding, and other applicable radiological health considerations. A partial listing of these publications is included in the reference and bibliography section.

The Manual was written with the assumption that the reader has a general knowledge of health physics such as that covered in the National Center for Radiological Health's training course, "Basic Radiological Health" *(1)*. For this reason no information is included on allowable radiation doses. It should be understood, however, that it is the allowable dose combined with the measurement of radiation intensity that determines whether or not a radiation area is safe to enter or occupy.

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# 3. PARTICLE ACCELERATORS: THEIR DISTINGUISHING CHARACTERISTICS, USES AND HAZARDS

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## 3.1 General

Accelerators are used to impart kinetic energy to electrically charged particles. The energies of the accelerated particles are sufficient to alter the molecular arrangement or the nuclear structure of the materials through which they pass. This kinetic energy is converted to potential energy within an altered nucleus, transferred to other particles, or converted to electromagnetic radiation.

Applications of accelerators make use of these processes. Radioactive isotopes result when an accelerated particle alters a nucleus leaving it in an unstable state. Properties of some plastics, resins, and crystalline materials are significantly changed by molecular or atomic dislocations due to bombardment by an accelerated beam. An appropriate target subjected to bombardment can be an intense source of electromagnetic radiation,such as X-rays which are useful in radiation therapy or industrial radiography.

Electric fields are used to exert the accelerating force on the charged particles which make up the internal beam of an accelerator. The electric field and the energy it imparts may result from a steady, high, DC voltage (up to several million volts), as in most potential-drop accelerators; it may result from traveling electromagnetic waves as in electron linear accelerators; or it may be a repeatedly-applied lower voltage, as in the cyclotron.

The unit used to define the kinetic energy of a particle is the electron-volt (eV). This is the energy gained by a particle having a charge equal to that of an electron in passing through a potential difference of one volt. Thus, an accelerator with a potential difference of V volts would accelerate a particle with two electronic charges to an energy of 2V eV. The mass of the particle determines the velocity which results from the acceleration. The velocity of heavier particles is less than that of light particles having the same kinetic energy.

Particle velocities can approach but not exceed the velocity of light. As the velocity of the particle increases its mass increases, approaching infinity as the velocity approaches that of light. Although there is a limit on velocity, there is none on the kinetic energy that can be given to a particle. For this reason, it is convenient to rate accelerators in energy rather than velocity.

Electrons to be accelerated are normally emitted by a heated filament or cathode. When ions are to be accelerated, they are created in a plasma discharge. However, other processes can create electrons and ions. These processes are important because they can cause the accelerator to produce a significant amount of accelerated beam (and radiation output), even though the normal source of electrons or ions is turned off. These processes are discussed in more detail in section 4.2.

The space through which the accelerated particles travel must be evacuated to prevent excessive loss of the beam as a result of collisions with gas molecules. Typical absolute pressures in accelerating chambers are $10^{-5}$ to $10^{-7}$ torr (mm Hg).

The internal beam is usually focussed by electromagnetic means. This focussed beam is directed onto a target inside the vacuum system to produce the desired external beam of X-rays or neutrons. In some cases, notably electron-beam radiation processing and more rarely, in electron-beam therapy, the internal electron beam is brought a short distance outside the vacuum system.

### 3.2 Potential-drop Accelerators

Potential-drop accelerators use a constant voltage to accelerate particles. They are typically constructed with an ion or electron source inside a "terminal" which operates at a very high voltage with respect to the target area of the machine which is at ground potential.

The high voltage terminal is mounted on an insulating support referred to as a "column" even though it may be horizontal. Every effort is made in the design of the machine to maximize the voltage that can exist along the column without sparking to any nearby grounded components or structures. The entire high voltage system may be contained in a pressure tank to take advantage of the increase in voltage which can be obtained from the use of an insulating gas under high pressure. Carbon dioxide, nitrogen or sulfur hexafluoride gases are typically used. Metal equipotential rings surround the column at intervals along its length. The terminal is covered by a smoothly rounded shell to avoid electric field concentrations which would reduce the voltage that can be held.

The accelerating particles pass from the ion source in the terminal through the evacuated accelerating tube. The tube as well as the insulators of the column are divided into sections along their length with each section connected to an equipotential ring.

The particles are accelerated through the voltage drop from the terminal to ground (or through two or three times the voltage drop in the case of a tandem machine). Terminal voltages up to about ten million volts are held in the largest pressurized machines. Below about a million volts, pressurization is not required.

### 3.2.1 Characteristics

Potential-drop accelerators use highly-developed special power supplies to generate the high DC voltage, and are usually named according to the type of power supply used.

Van de Graaff: Van de Graaff accelerators use a belt made of an insulating material moving at a high speed to carry electrical charge from the grounded end of the insulating column into the high voltage terminal.

At the operating voltage, leakage, corona, and beam currents remove charge at the rate that it is delivered by the belt. The operating voltage can be varied by changing the amount of charge delivered or by changing the leakage. Such controlled leakage may also be used to stabilize the operating voltage within close tolerance limits.

The charging supply delivers current to the belt at a moderate voltage by corona from a row of pointed electrodes. These electrodes spray charge uniformly onto the belt. A similar set of electrodes remove the charge at the high voltage terminal. When the charging supply is turned off, no charge is delivered. However, charging the terminal may occur by other effects, such as friction. These stray charges may accumulate at the terminal and develop a very high voltage. This potential on the terminal may be sufficient to accelerate a "dark current" of ions or electrons (see 4.2.3). Thus this type accelerator can produce hazardous radiation levels with both the ion source and charging supply turned off if the belt is running. The schematic of a Van de Graaff accelerator is shown in Figure 1.

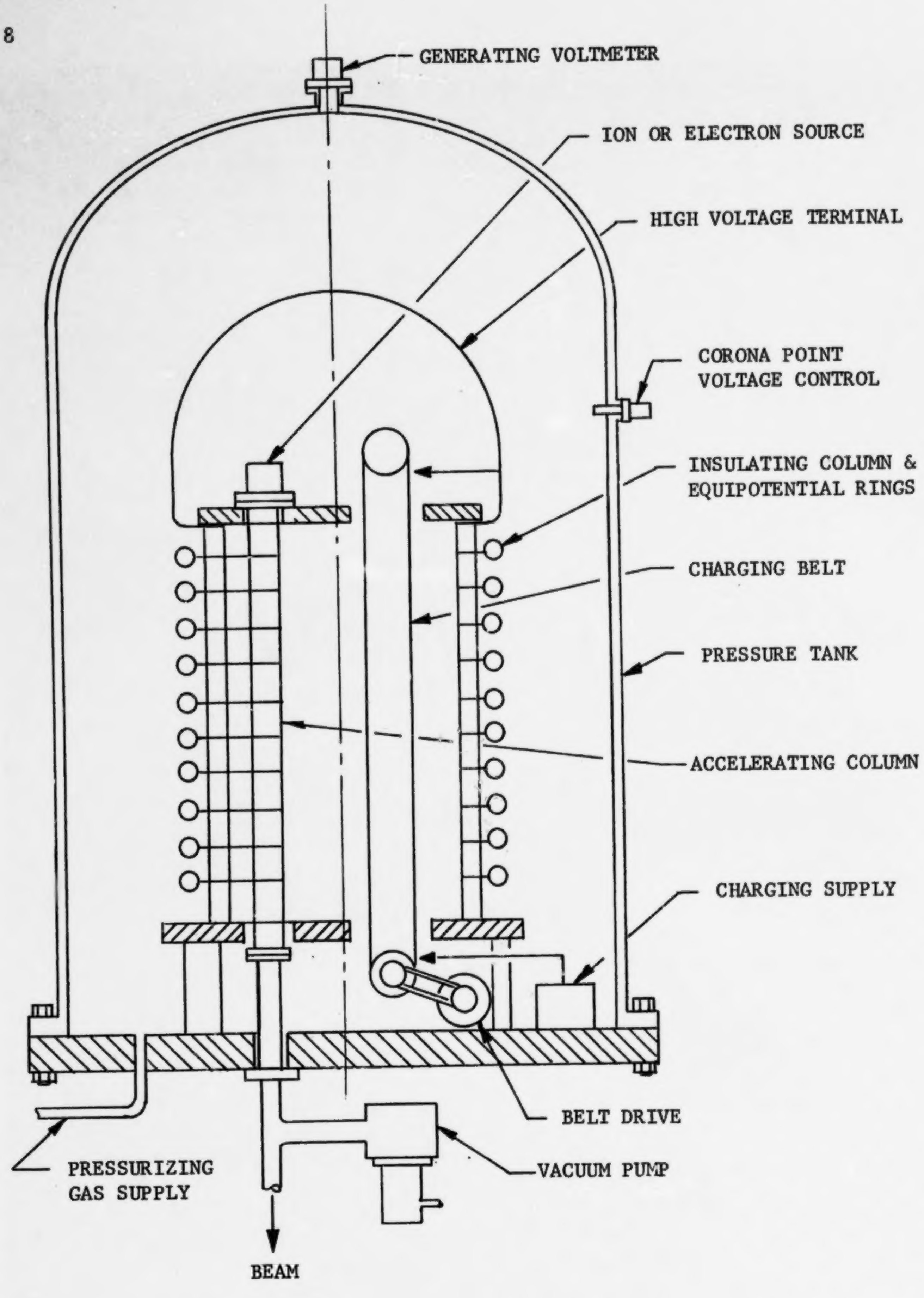

GENERATING VOLTMETER
ION OR ELECTRON SOURCE
HIGH VOLTAGE TERMINAL
CORONA POINT VOLTAGE CONTROL
INSULATING COLUMN & EQUIPOTENTIAL RINGS
CHARGING BELT
PRESSURE TANK
ACCELERATING COLUMN
CHARGING SUPPLY
BELT DRIVE
PRESSURIZING GAS SUPPLY
VACUUM PUMP
BEAM

Figure 1. Schematic of a Van de Graaff Accelerator

Van de Graaff accelerators are noted for their ability to maintain the energy of the beam within close tolerances. They are the most widely used type of accelerator. Van de Graaff accelerators are used to produce X-rays for radiography, neutron beams for activation analysis, ion and electron beams for research, and electron beams for industrial processing.

Cockcroft-Walton: The power supply of a Cockcroft-Walton accelerator consists of a large number (20 or more) of individual rectifiers arranged in cascade with the input power to each stage obtained from the stage below it. High frequency primary power is often used to reduce the size of components and the voltage ripple at the terminal. Cockcroft-Walton accelerators produce beams of lower energies than those of the Van de Graaff but of comparable intensities and for similar applications. Cockcroft-Walton accelerators are often not pressurized. The schematic of a Cockcroft-Walton accelerator is shown in Figure 2.

Dynamitron: The Dynamitron makes use of a cascade voltage-multiplying circuit similar to the Cockcroft-Walton generator, but with the stages driven in parallel through high voltage capacitors instead of in series. A radio-frequency power source is used to charge the capacitors.

Dynamitrons are ordinarily designed for higher voltages than Cockcroft-Walton accelerators and are pressurized. The schematic of a Dynamitron is shown in Figure 3.

Resonant Transformer: High voltage transformers are also used for potential drop accelerators. In the "Resonant-Transformer" accelerator, taps from the secondary winding of an air-core transformer are connected to the equipotential rings along the accelerating tube. The transformer is designed to resonate with circuit capacitances at the frequency of the primary voltage. The beam output of this type of accelerator is pulsed at the supply voltage frequency, and varies in energy with the sinusoidal change of voltage during the beam pulse. Accelerators using this type of voltage supply are used in applications in which the varying beam energy is not objectionable. Such applications occur in radiography or electron beam processing. Figure 4 is the schematic of a resonant transformer accelerator.

Insulating Core Transformer: A second type of transformer accelerator is the "Insulating-Core Transformer" or ICT shown schematically in Figure 5. This machine uses a transformer core separated into insulated segments. Secondary windings link the core, each driving its own rectifier. The rectifier outputs are connected in series to produce the high voltage. The accelerating column may be directly connected to the high voltage terminal or may be physically separated from the transformer and connected to it by a high voltage shielded cable. These accelerators can be designed to provide an output voltage with only small amount of ripple.

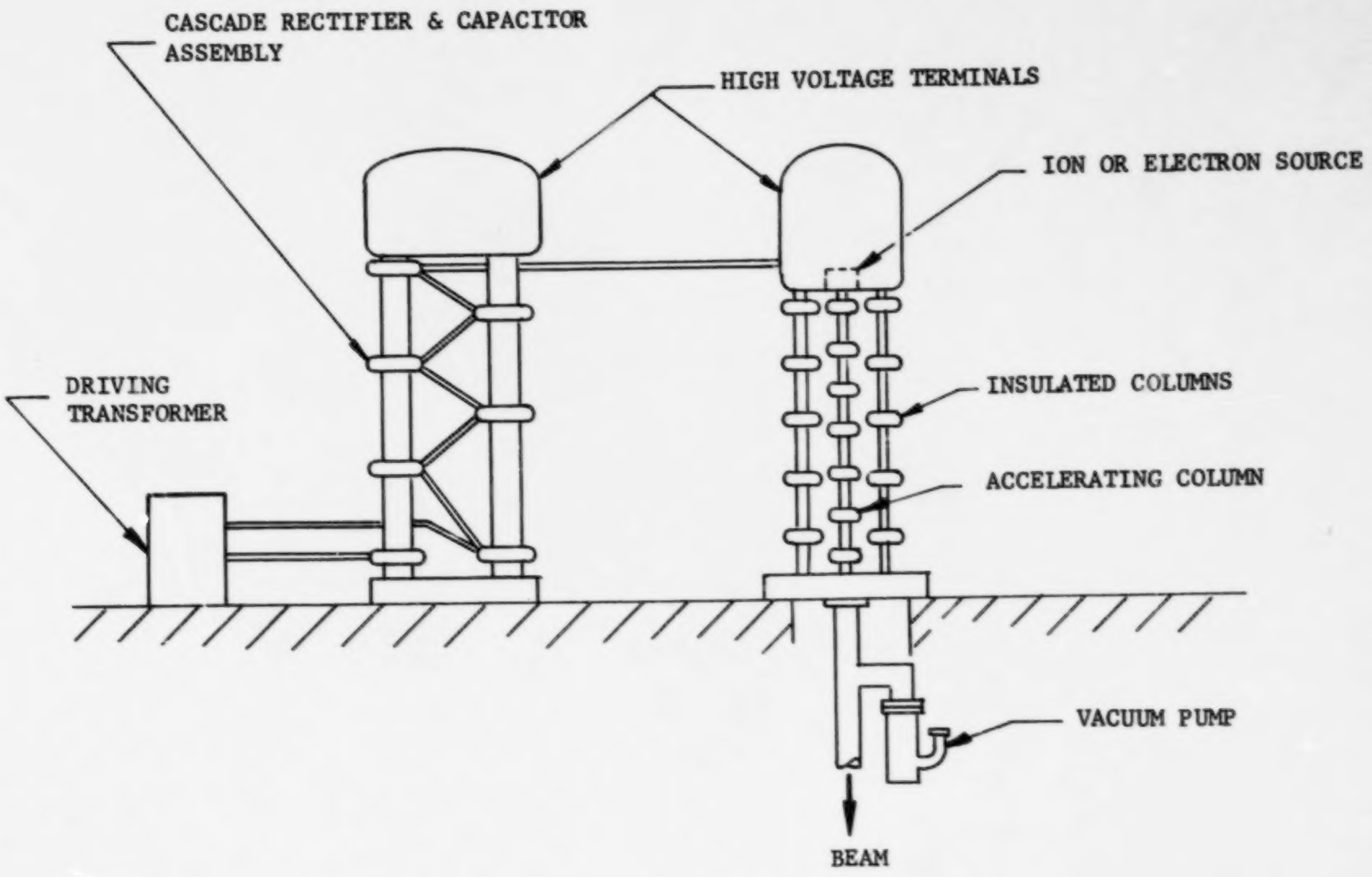

CASCADE RECTIFIER & CAPACITOR ASSEMBLY
HIGH VOLTAGE TERMINALS
ION OR ELECTRON SOURCE
DRIVING TRANSFORMER
INSULATED COLUMNS
ACCELERATING COLUMN
VACUUM PUMP
BEAM

Figure 2. Schematic of a Cockcroft-Walton Accelerator

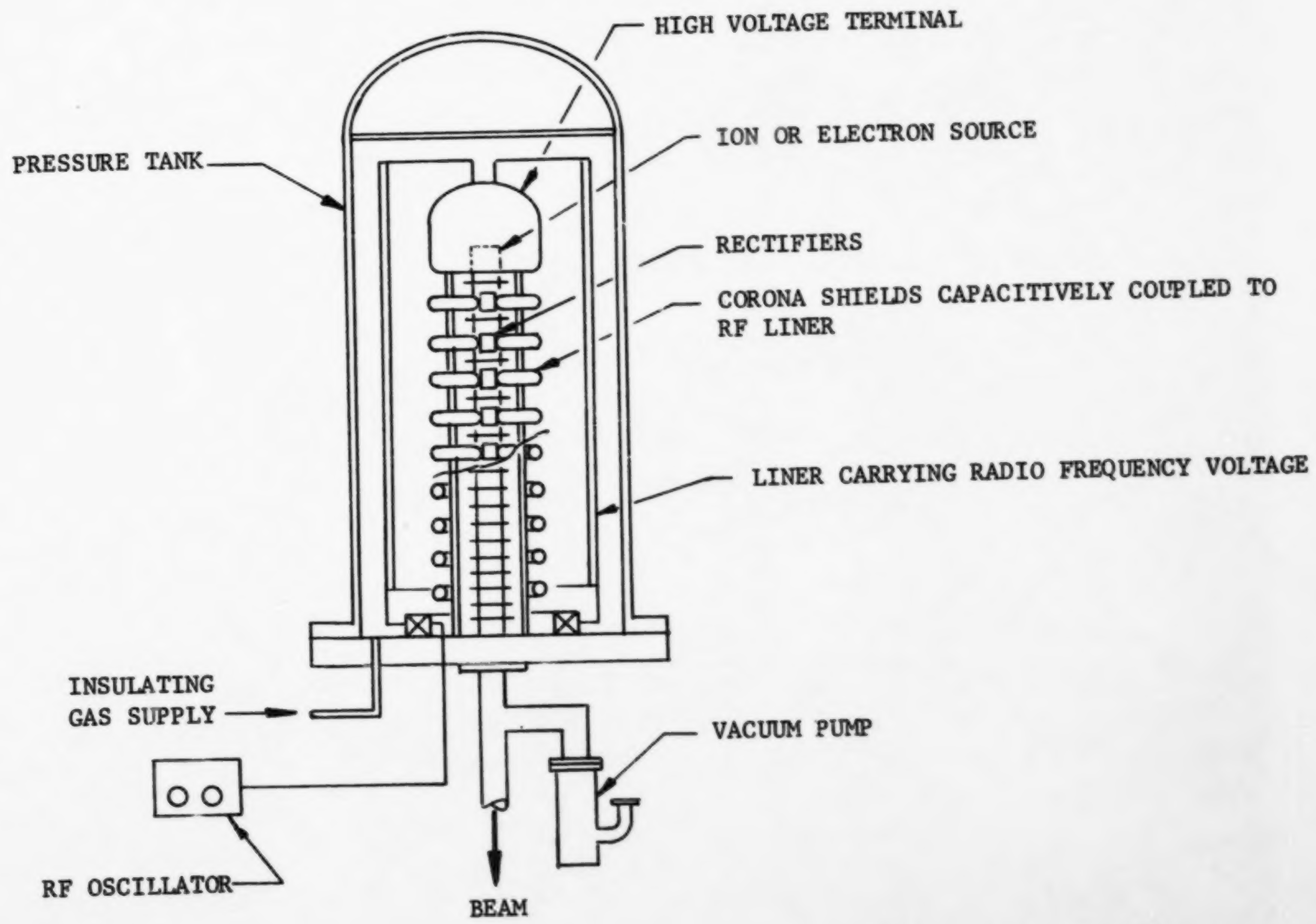

HIGH VOLTAGE TERMINAL
ION OR ELECTRON SOURCE
PRESSURE TANK
RECTIFIERS
CORONA SHIELDS CAPACITIVELY COUPLED TO RF LINER
LINER CARRYING RADIO FREQUENCY VOLTAGE
INSULATING GAS SUPPLY
VACUUM PUMP
RF OSCILLATOR
BEAM

Figure 3. Schematic of a Dynamitron Accelerator

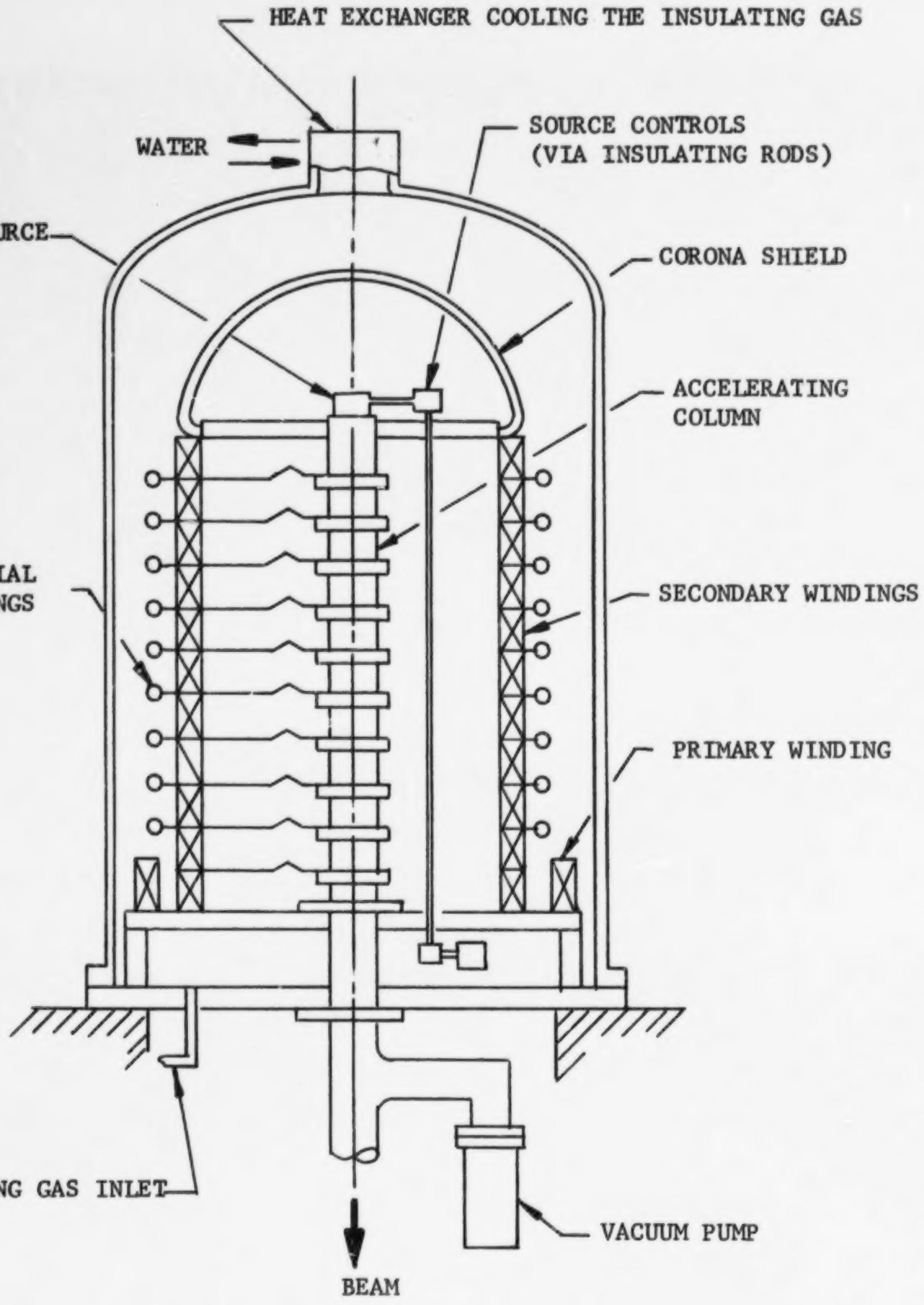

HEAT EXCHANGER COOLING THE INSULATING GAS
WATER
SOURCE CONTROLS
(VIA INSULATING RODS)
ELECTRON SOURCE
CORONA SHIELD
ACCELERATING
COLUMN
EQUIPOTENTIAL
RINGS
SECONDARY WINDINGS
PRIMARY WINDING
INSULATING GAS INLET
VACUUM PUMP
BEAM

Figure 4. Schematic of a Resonant Transformer Accelerator

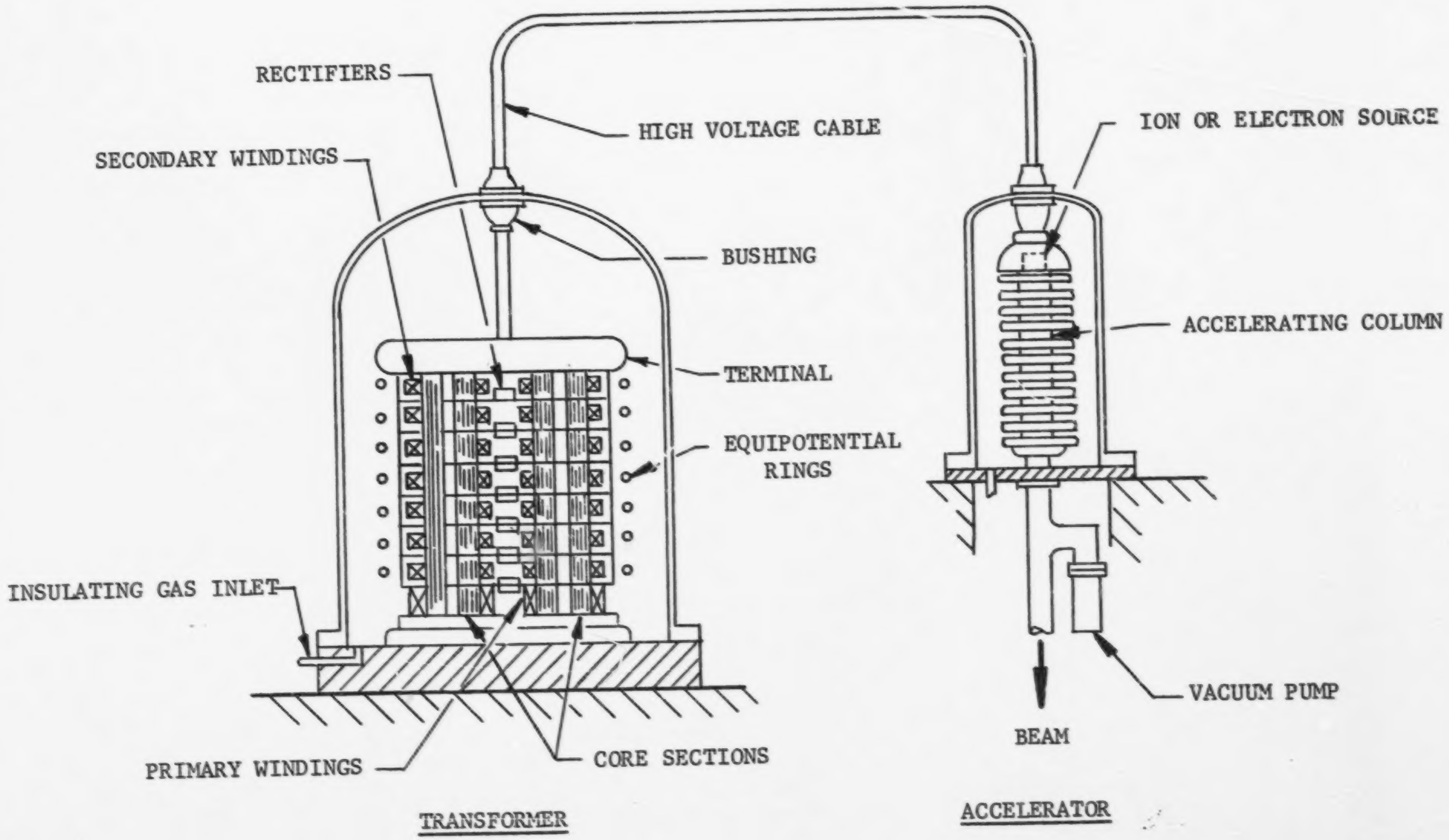

RECTIFIERS
SECONDARY WINDINGS
HIGH VOLTAGE CABLE
BUSHING
TERMINAL
EQUIPOTENTIAL RINGS
INSULATING GAS INLET
PRIMARY WINDINGS
CORE SECTIONS
TRANSFORMER
ION OR ELECTRON SOURCE
ACCELERATING COLUMN
VACUUM PUMP
BEAM
ACCELERATOR

Figure 5. Schematic of an Insulating Core Transformer Accelerator

### 3.2.2 Uses

The major uses of potential drop accelerators are radiography, activation analysis, food sterilization and preservation, industrial processing, radiation therapy and research. X-rays are electromagnetic radiation produced by changes in the energy of electrons within an atom. Such rays can be very energetic and of short wavelength, enabling them to penetrate matter to considerable depths. The use of X-rays for medical diagnosis is familiar; these rays typically have energies of about 125 keV. X-rays produced by the accelerators discussed here are of much higher energy and have much greater penetrating ability. These high energy X-rays can be used to inspect the interior of thick metal castings and weldments, and of most other opaque material. As in diagnostic medicine, the rays which pass through the material form an image on photographic film which can clearly define voids or internal structure. X-rays for radiography are produced by the bombardment of a heavy-metal target, usually by an intense and sharply-defined electron beam for maximum image sharpness on the film.

The rate of decay and the nature and energy of the decay products of each radioactive isotope are a characteristic of that isotope. A substance which has been made artificially radioactive can be identified by analysis of its radiation, and the amount of each isotope present can be determined. Through activation analysis the presence of certain elements can be detected even though they are present only in trace quantities. In activation analysis the substance to be activated is exposed to a flux of energetic particles, usually neutrons, which can be obtained by bombardment of a suitable target with an ion beam from an accelerator. Potential-drop accelerators, and in particular Cockcroft-Walton accelerators, are usually used for this purpose.

X-rays and electrons can be used to destroy bacteria without the use of heat. This process may be used on fruits, vegetables, or meats to prevent spoilage for extended periods. X-rays and electrons can also be used to inhibit sprouting of vegetables.

Irradiation of polymers such as elastomers, resins, and plastics cause the formation of cross linkages between molecules. Such beneficial effects as increased hardness, toughness and temperature resistance can thus be obtained. Paints and adhesives can be rapidly cured by radiation. X-ray or electron beams are also used for sterilization or surgical sutures and medical supplies.

Radiation produced by accelerators can be used to retard or destroy malignant growths. Exact beam positioning, collimation, and rotation can permit high radiation dosages to be applied to a deeply submerged tumor while damage to surrounding tissue is kept relatively low.

Accelerators are widely used in physical, medical and biological research.

### 3.2.3 Hazards

Potential-drop accelerators, especially in the energy range of a few MeV, are capable of very high beam intensities which can constitute a serious radiation hazard. The danger of exposure to the external beam and the secondary radiation that the beam generates is, of course, the principal hazard. In addition, if the beam passes through air, there is danger from ozone formation and the production of radioactive gases. If tritium targets are used, there is a possibility of leakage and contamination of the vacuum system and components associated with the target. X-rays may be produced at the target end of the machine, and also at the high-voltage terminal by the "back-streaming" of electrons.

When machines are used at relatively low intensities only minimal shielding may be required. Personnel may become careless if they consider the radiation hazard as negligible. This neglect may lead to improper notice of changed conditions or more serious hazards in certain areas. Careless habits must be avoided. All radiation-producing machines must be respected for their maximum radiation capabilities rather than their customary operating conditions.

As radiation may be produced by dark current and self-charging processes, it should be remembered that, in general, any accelerator can produce hazardous radiation levels if the accelerating voltage is turned on even though the ion source or electron source is off. High voltage should be assumed to be present in a Van de Graaff accelerator whenever the belt is running, even though the charging supply is off.

In industrial applications, unskilled workmen who may use an accelerator cannot be expected to completely understand the physics of radiation hazards. Often such people are ingenious in circumventing accepted safety practices when they are concerned only with getting a particular job done or with reducing their own effort or inconvenience. Personnel must be protected from themselves by the use of interlocks and warning devices as described in Section 4.6.

Among the more typical industrial hazards are those involved in the use of high-pressure gases and in handling parts of the large, heavy tanks that are usually used to contain the high-voltage components. Electrical power supplies present high-voltage hazards, especially in the case of air-insulated machines. There may also be a serious electrical shock hazard due to large capacitors charged to high voltage.

## 3.3 Electron Linear Accelerators (Linacs)

In an electron linear accelerator (illustrated in Figure 6) a relatively small amount of energy is required to accelerate the electrons to nearly the speed of light. Further increase in kinetic energy results

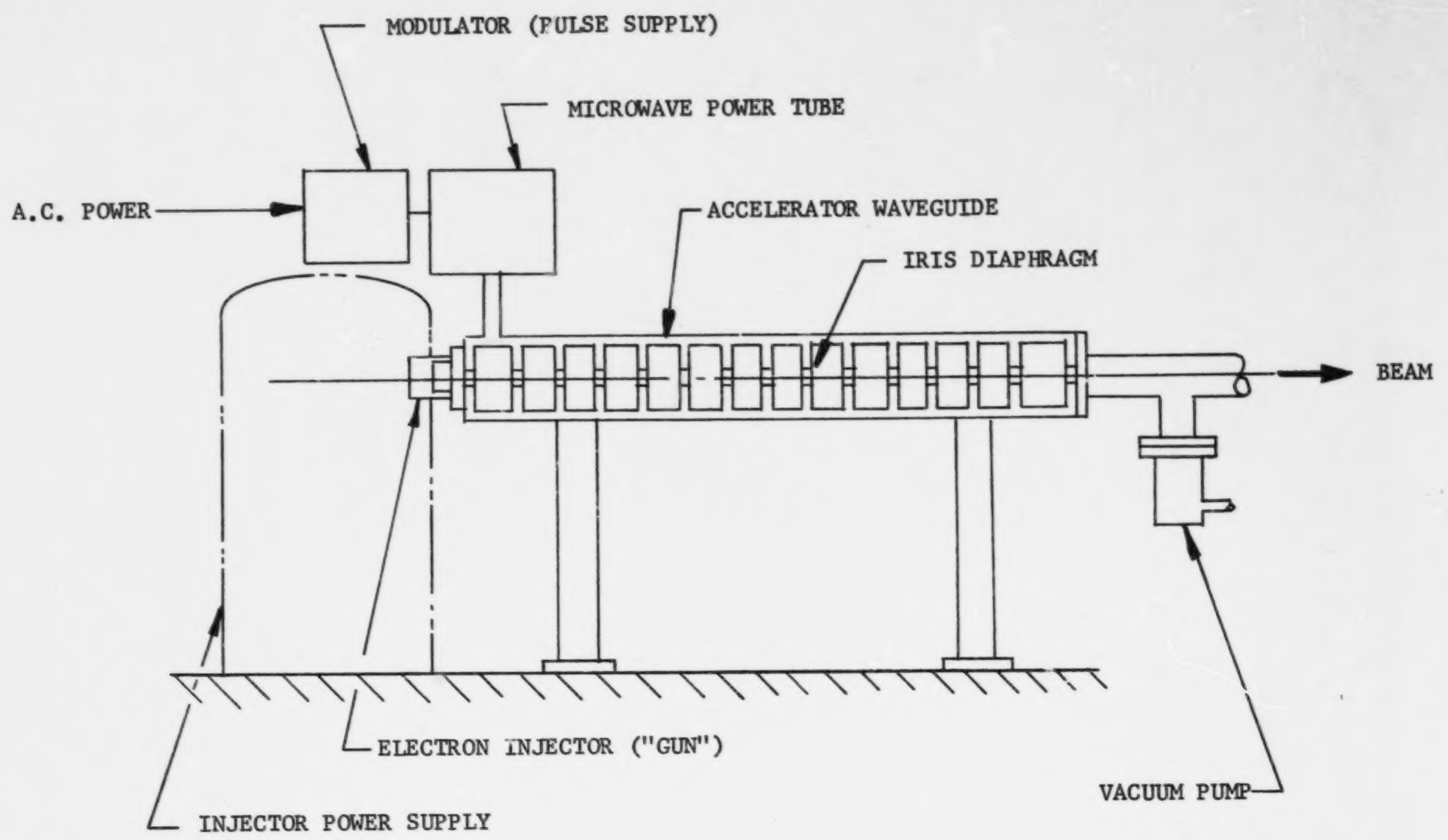

MODULATOR (PULSE SUPPLY)
MICROWAVE POWER TUBE
A.C. POWER
ACCELERATOR WAVEGUIDE
IRIS DIAPHRAGM
BEAM
ELECTRON INJECTOR ("GUN")
VACUUM PUMP
INJECTOR POWER SUPPLY

Figure 6. Schematic of an Electron Linear Accelerator

primarily in increasing the mass of the particle and has little effect on its velocity. Thus it becomes feasible to produce the accelerating potential by waves traveling at constant velocity which can be generated in radiofrequency waveguides.

### 3.3.1 Characteristics

The accelerating waveguide of a linac consists of a circular tube containing a series of disks along its length. Each disk has a central hole through which the electron beam passes.

The radiofrequency power source which drives the waveguide must supply very high power in short pulses. The RF power source uses components similar to those used in high power radar equipment.

Electron linacs in the region of 10 MeV or below are usually used to produce intense electron beams. Radiation intensities are so high that even a few seconds exposure to the beam or its secondary products can be lethal. What might be only a disturbing incident with many accelerators could be a fatality with an electron linac.

Since neutron production by electrons does not generally occur below about 15 MeV, the most common radiation hazard is from the primary electron beam where it is accessible in air and from the X-rays coming from the target. X-rays are also produced by the high voltage on the klystron tubes used in the radio frequency power supplies. A method of estimating the radiation level produced by klystrons is given in Appendix A.

### 3.3.2 Uses

Linear accelerators are widely used in research by university, government, industrial, and medical laboratories. They are frequently used to produce X-rays for nondestructive inspection of large or thick weldments and castings, and for inspection of rocket propellants. Electron and X-ray beams produced by electron linear accelerators and potential-drop accelerators have similar uses. Specifically, these machines are used mainly for radiography, food sterilization and preservation, industrial processing, radiation therapy and research.

### 3.3.3 Hazards

Electron linacs are often used for industrial processing where precautions necessary with unskilled labor must be observed.

The scattering and buildup of X-rays and the effect of skyshine (Section 4.5.5) make the radiation field intensity outside the shielding of high power electron linacs difficult and uncertain to predict. Careful radiation survey measurements are necessary to insure against overexposure of personnel. Radiofrequency signals from accelerator power source may cause survey instruments to give erroneous readings. The effect can be minimized by using instruments which are shielded and insensitive to radiofrequency signals. It is especially important to check all occupiable spaces within a hundred feet or so of the target, whether they are actually part of the accelerator building or not. Basements or attics should be surveyed because they may be occupied by personnel unaware of the possibility that radiation may be present.

Due to multiple scattering, low-energy electrons travel many feet in air and will flow around corners and through crevices in a manner similar to a fog. Fortunately only a few millimeters of metal are required to stop these electrons. However, it is essential that all apertures be closed that would otherwise provide too short a path between the target and occupied areas. Unused conduit should be plugged. Doors leading to the target room and accelerator room should be sealed by weatherstripping. Ventilation ducts should be checked to determine if there are any potential paths for radiation to leak out that could produce a hazard to operating personnel.

It must be remembered that electron beams may produce extremely high exposure rates and can produce serious effects in a fraction of a second. Owing to the ease with which electron beams are scattered, no room should be entered in which intense electron beams are in use. Serious consequences have occurred due to the neglect of this simple and fundamental precaution.

Interlocks should be provided on all doors and passageways leading to irradiation and accelerator rooms. Emergency stop systems should also be incorporated in these rooms in the event personnel are trapped in one of these potentially dangerous areas. The RF and injector power should be interrupted when these interlocks or emergency systems are activated. Linacs that have an energy above 10-12 MeV can become radioactive near the output end. Radiation measurements should be made periodically to ascertain whether hazardous induced radioactivity exists or is developing.

An important source of industrial hazard associated with electron accelerators is the high voltage equipment required. The electron gun of a linac is often powered by the type of supply used in a potential-drop accelerator and presents the same hazards. Klystron tube voltages are over a hundred kilovolts and must have appropriate protection. High-voltage capacitors also present dangers.

Fire hazard may exist from flammable oil used to insulate high voltage transformers driving the klystrons or the electron gun. The installation requirements for such tanks are covered by the National Electric Code.

## 3.4 Cyclotrons

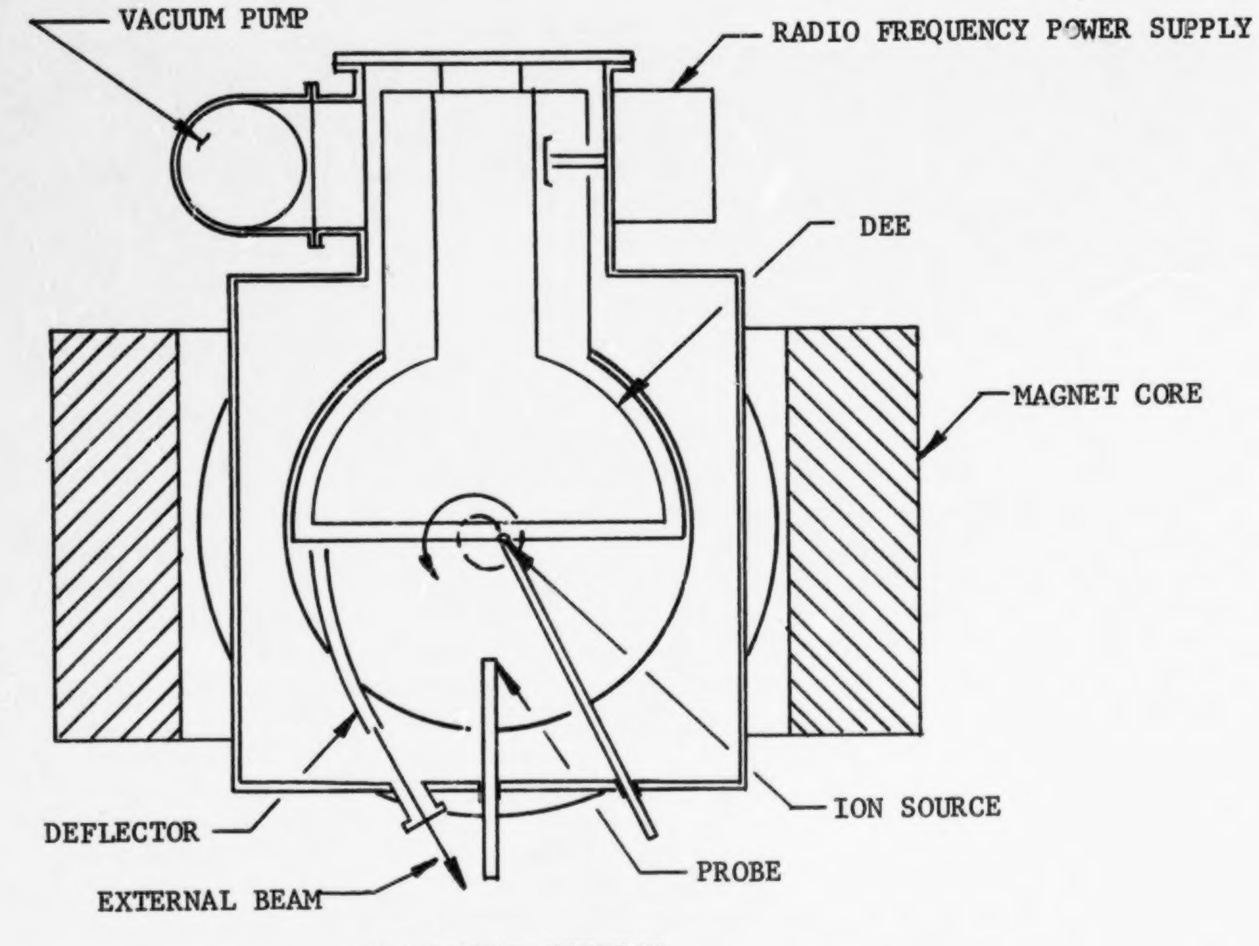
### 3.4.1 Characteristics

The cyclotron, as illustrated in Figure 7, uses a magnetic field to confine the beam particles to a plane, nearly circular, path. The path is enclosed by one or two hollow semicircular electrodes called "dees" because of their shape. An RF voltage is applied between the dees at the frequency at which the ions rotate, which is constant in the conventional cyclotron. As the voltage between the dees alternates, particles are accelerated as they enter and leave the dees. The RF voltage is typically of the order of 100 kilovolts, so the particles may receive up to 200 KeV per electron charge on each complete revolution. The particles start at the ion source at the center of the magnetic field. As their energies increase, their path radius increases and the particles spiral outward. Since the particles make many revolutions and acquire energy twice with each revolution, their final energy may become very large compared to the voltages on the electrodes. Cyclotrons produce higher energy particles than potential-drop machines, in which the particles pass through a much larger accelerating voltage but do so only once or at most a few times.

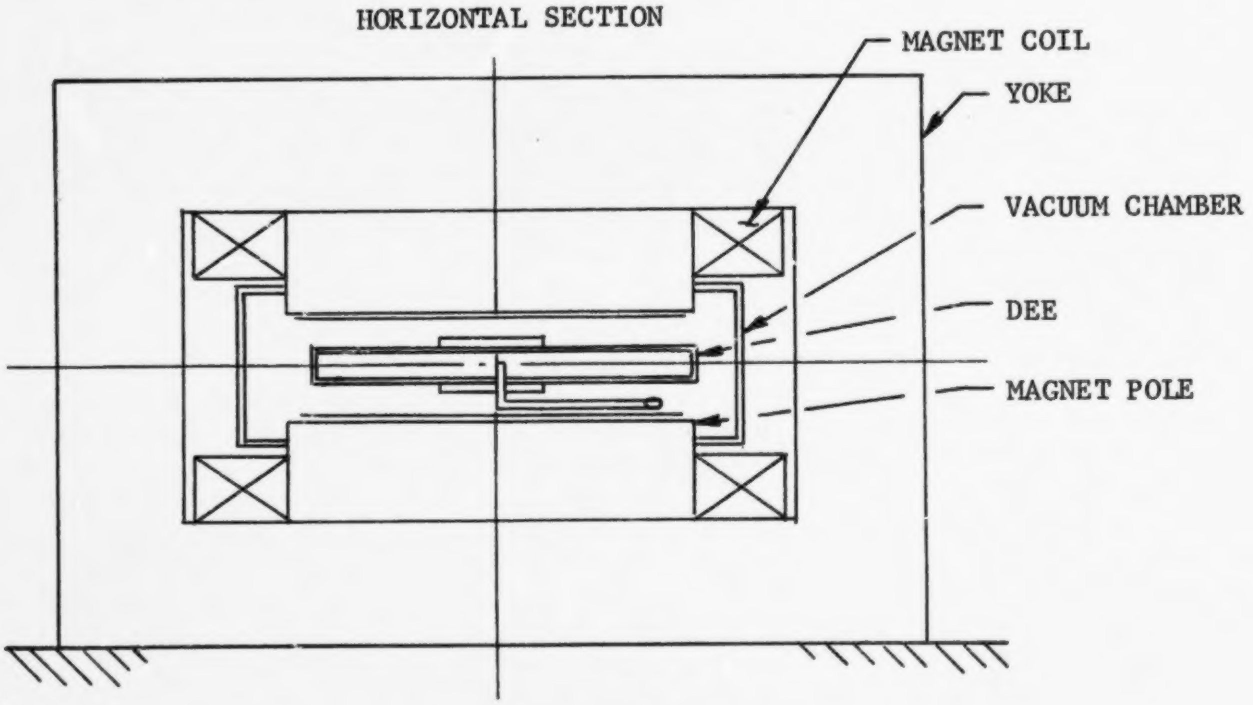
Extracting the beam from the cyclotron is more difficult than from accelerators in which the beam path is straight. If the beam is not used internally, it must be deflected tangentially from the machine. This is usually done with a high voltage electrode which produces a radial electric field opposing the magnetic field and tending to straighten the beam orbit. During extraction, a portion of the beam strikes the structure of the machine, causing heating and induced radioactivity, particularly at the leading edge of the thin blade (septum) which forms the inner surface of the extraction channel.

The foregoing description applies to the conventional cyclotron. Synchrocyclotrons compensate for the relativistic mass increase of particles as they reach high energy by reducing the acceleration frequency. Because the frequency must return to normal after each cycle, these cyclotrons deliver beams in pulses. Isochronous cyclotrons, also called azimuthally varying field (AVF) or sector focussed cyclotrons, use a constant accelerating frequency and focus the particles by means of wedge-shaped sectors on the magnet poles. Cyclotrons are most often used where ions of energies exceeding about 15 MeV are required.

Cyclotrons accelerate the heavy particles, protons, deuterons, and alpha particles, but not electrons. At the usual cyclotron energies, secondary beams of high neutron intensities and large gamma fluxes are possible.


VACUUM PUMP
RADIO FREQUENCY POWER SUPPLY
DEE
MAGNET CORE
DEFLECTOR
ION SOURCE
PROBE
EXTERNAL BEAM

HORIZONTAL SECTION


MAGNET COIL
YOKE
VACUUM CHAMBER
DEE
MAGNET POLE

VERTICAL SECTION

Figure 7. Schematic of a Cyclotron

### 3.4.2 Uses

Cyclotrons are most commonly used in physics laboratories, as well as in chemical and medical facilities. They can be used to produce short-lived isotopes for diagnostic measurements and medical therapy. Fluxes of fast and thermal neutrons can be produced with the cyclotron to be used for activation analysis.

Accelerator protons, deuterons or heavier ions may be used to produce radioactive isotopes by bombardment of any element if the accelerated particles have enough energy for the reaction involved. Accelerators, at one time, provided the only means of making isotopes. At present, most radioactive material is produced as by-product material from nuclear reactors. However, increased use of accelerators, and in particular cyclotrons, is anticipated for the production of isotopes with short half-lives which must be used in close proximity to where they are produced.

### 3.4.3 Hazards

The complex geometry of the structural materials composing and surrounding the cyclotron, the neutron flux and energy, the long-lived activity of the machine, and the time delay before one can enter the cyclotron enclosure, are factors that determine the radiation fields to be encountered. The neutron flux and energy are functions of the type of target being bombarded, the energy and intensity of the ion beam, and the type of primary particle being accelerated.

Cyclotrons generally become extremely radioactive, which leads to difficulties in avoiding overexposure during maintenance. As an example of the induced radioactivity associated with cyclotron operation, decay curves for gamma radiation following shutdown of the University of California 60-inch cyclotron after operation with 24 MeV deuterons are shown in Figure 8. The primary half-lives observed are 5 minutes, 38 minutes, 2.6 hours and 12.8 hours. These are probably radiations from $^{66}$Cu, $^{63}$Zn, $^{65}$Ni, and/or $^{56}$Mn, and $^{64}$Cu respectively *(2)*. It is apparent that it would be wise to delay maintenance operations on this cyclotron for at least eight hours and preferably over a weekend.

Very large amounts of residual radioactivity can also be induced in the cyclotron target. Such radioactivity is more easily dealt with than the residual activity in the accelerator itself. If the target can be removed, it should be placed in an adequately shielded storage area. Handling tools should be used which will keep the source of radiation as far as practical from the person handling the target. If the target cannot be removed it should be shielded in place or otherwise isolated with a controlled area set up around it.

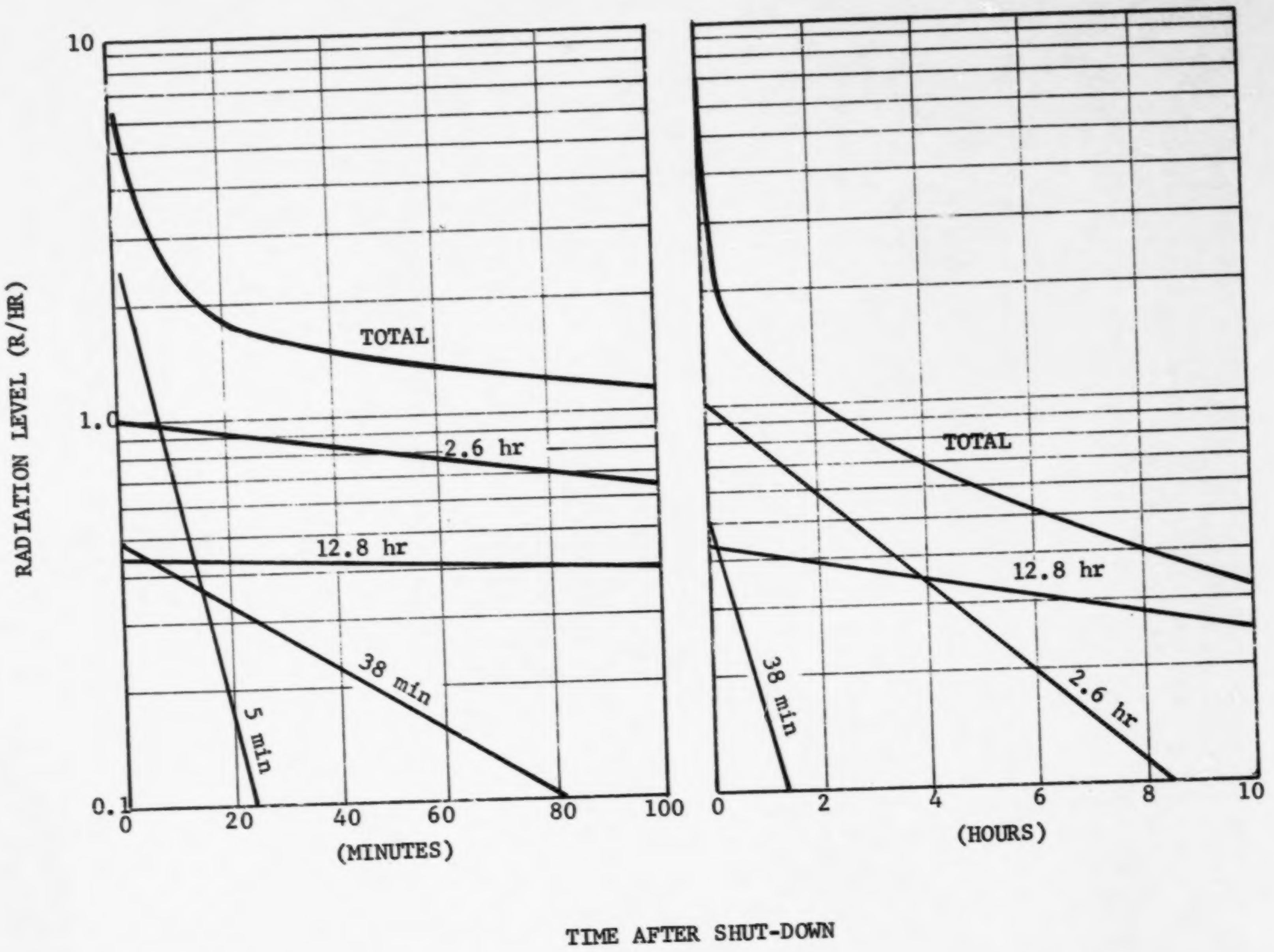


Figure 8. Gamma-Radiation Intensity as a Function of Time after Cyclotron Shut-down, as measured Beside the Vacuum Tank of the 60-inch Cyclotron (2)

Maintenance personnel working on cyclotrons should wear pocket dosimeters in addition to film badges. Accumulated doses should be recorded by a responsible person. Proper handling and storage of the radioactive parts, particularily the dees, deflectors, and target supports, is also important.

Most of the radiation near the cyclotron is a result of the beam striking the structure, especially the deflector and exit port, and sometimes the dees. To reduce residual radioactivity, carbon blocks are used to absorb a beam which would otherwise strike metal components.

Operations which require removing radioactive metal by filing, drilling, grinding, sanding, etc. should be closely monitored. Grinding and sanding operations may require temporary hoods to confine the particles which are removed. Ventilation may also be required to prevent radioactive particles from being inhaled, ingested or spread throughout the building.

The large cyclotron magnet gives rise to the magnetic hazards discussed in Section 5.3.3. The heavy equipment required around a cyclotron constitutes a handling hazard. The electrical system may involve extreme hazards due to the use of high voltages and unconventional circuits. Radiation warning and interlocking for personnel protection must be carefully designed, especially where a cyclotron is used by several research groups, only one of which may be using the machine while the others require access to their equipment.

## 3.5 Betatrons

### 3.5.1 Characteristics

The betatron is a magnetic-induction accelerator which makes use of a varying magnetic field to accelerate electrons. The principal parts of a betatron are the iron-core magnet, the toroidal vacuum chamber, and the electron injector. Figure 9 is the schematic diagram of a betatron. Electrons are injected tangentially into the vacuum chamber, and are accelerated by the changing flux of the betatron magnet. In the design of the betatron, the rate of change of the magnet flux and the magnetic field at the orbit radius are related to maintain a constant radius for the accelerating electrons. The beam is produced in pulses at the frequency of the magnet power which is usually sixty cycles per second.

### 3.5.2 Uses

The betatron is used in many of the same applications as linacs and electron-accelerating potential-drop accelerators. As an X-ray source it is used for radiography of heavy castings and medical therapy. It may be used as a research tool in a few instances where photon energies of the order of 30 MeV are of interest. It is not usually used for radiation processing or food sterilization and preservation.

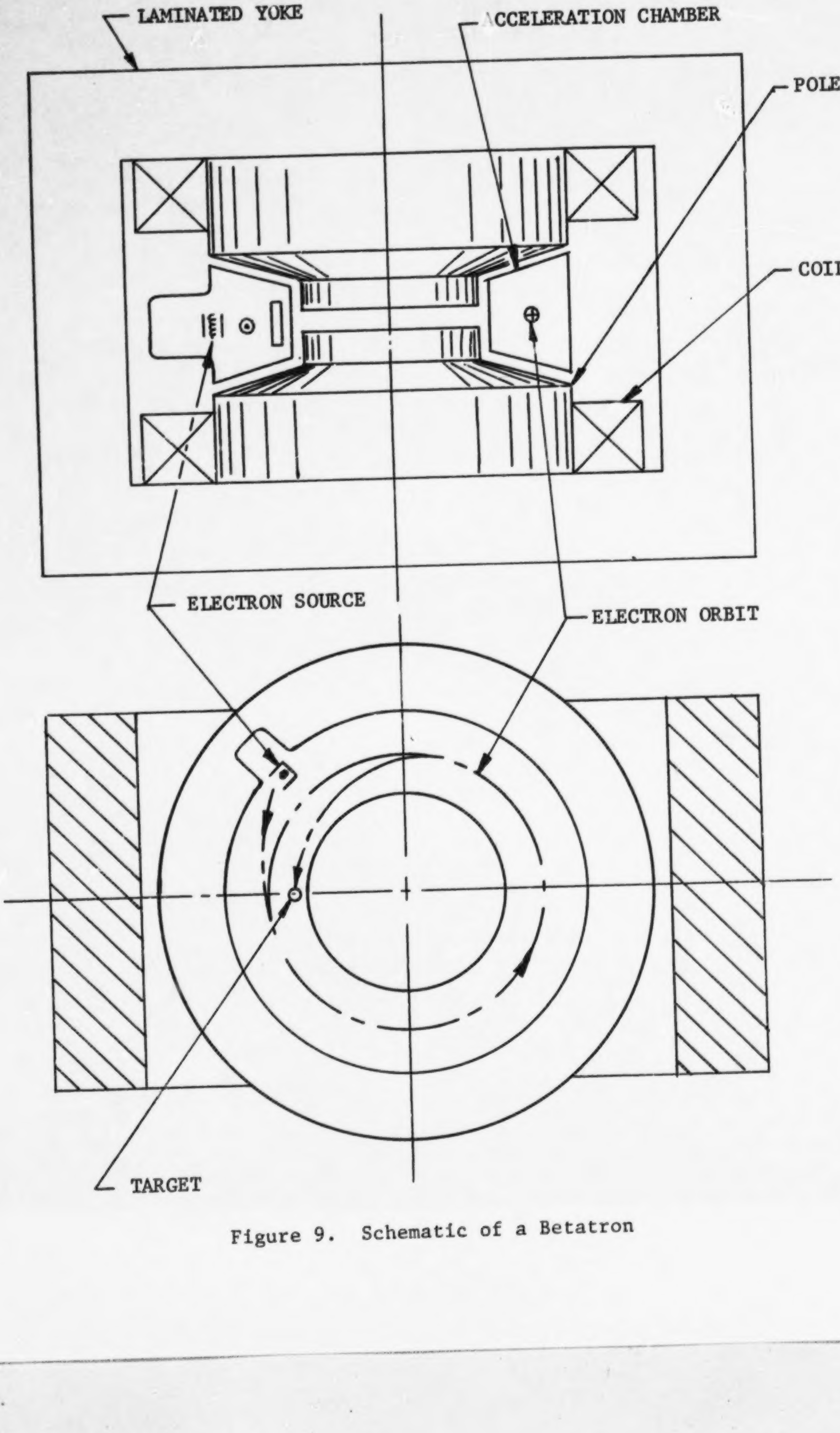

LAMINATED YOKE
ACCELERATION CHAMBER
POLE
COIL
ELECTRON SOURCE
ELECTRON ORBIT
TARGET

Figure 9. Schematic of a Betatron

### 3.5.3 Hazards

Betatrons produce electron beams and X-rays similar to those of electron linacs. The precautions required are, therefore, similar to those for the electron linear accelerator.

A feature of betatrons not common to linacs is the power supply for the magnet. The magnet is resonated by a large capacitor bank, which can store enough energy to cause a serious electrical fire if it is accidentally dissipated in a short circuit.

Capacitor banks present unusual hazards because they can store energy for long periods of inactivity and release it almost instantaneously. Because capacitors are connected in parallel, an internal short-circuit in any one frequently allows all the energy to be dissipated in the defective unit. This can result in explosive rupture of the shorted capacitor, with flying fragments and possible fire. Proper electrical safety practices reduce the hazards satisfactorily. These safety practices should be carefully followed. Persons who are not properly trained should not be allowed to enter the capacitor area.

The parts of a betatron exposed to the full beam can become radioactive. The extent of this hazard should be determined by periodic radiation surveys.

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## 4.1 General

The radiation from accelerators and radioactive materials is classified as ionizing radiation. This is in contrast to non-ionizing radiation, such as visible light and radio waves which do not ionize the material through which they pass. Ionization is the process of removing electrons from atoms. The result of ionization is the production of free electrons with their negative charges and of ionized atoms with positive charges. Thus, a portion of the material through which the ionizing radiation passes is separated into electrically charged atoms and negatively charged electrons.

The ionized atoms are much more active chemically than the neutral atoms undisturbed by the radiation. These chemically active atoms can form compounds that interfere with the processes of cell division and metabolism. The degree of damage suffered by an individual exposed to radiation is affected in a complicated way by the type, intensity and energy of the radiation to which an individual is exposed.

Ionizing radiation in accelerator installations may be classified according to its source, as primary radiation, secondary radiation, stray radiation, and induced radioactivity.

The beam of particles which is accelerated by the particle accelerator is the primary radiation. Particles commonly used as projectiles are electrons, protons, deuterons and alpha particles. When the primary beam strikes a target or other material, secondary radiation is produced.

During the acceleration process a portion of the primary beam may strike the walls of the accelerating chamber or other system components. This interaction results in the production of secondary radiation identified as stray radiation. All radiation resulting from the interaction of the primary radiation with matter other than the radiation from induced radioactivity is called secondary radiation, even though it may be the result of several successive conversions from one form of radiation to another.

When the accelerator beam is turned off, the primary and secondary radiation will cease. However, other radiation hazards due to induced radioactivity may exist. The atoms of materials irradiated may have been excited to an unstable state or new unstable atoms may have been produced. The unstable atoms will return to a more stable state after a time described by a characteristic half-life and with the emission of radiation. The radiation may consist of the emission of electrons, positrons, alpha particles, or gamma rays, or combinations of these rays and particles.

Personnel must be protected from ionizing radiation by proper design of the accelerator facility. Radiation shielding, interlock systems, and warning devices should be considered in early planning stages. Periodic inspection of these systems is necessary to insure their proper operation and integrity. Recommendations are made in Section 4.5 with regard to radiation shielding and in Section 4.6 with regard to interlock systems and warning devices.

Operation and maintenance personnel who work in accelerator installations must be instructed in radiation safety, as well as in industrial safety. Radiation safety training is particularly important if a health physicist is not employed in the installation.

## 4.2 Accelerator Sources of Radiation Hazards

### 4.2.1 Primary Radiation

The primary radiation always consists of charged particles because the charge is necessary for the accelerating process. The primary radiation is always directed and is usually focussed into a beam. The primary radiation exists as the "internal beam" inside the machine, and as the "external beam" which emerges from the accelerator, usually by passing through a thin metal foil at the beam exit port. The external beam is usually focussed to a small diameter, and directed onto a target. For these reasons the primary radiation occupies a very small volume, and its energy is very concentrated. Some accelerators spread the primary radiation over a larger area (for example, in the industrial processing of sheets of plastic or the sterilization of surgical sutures which pass through the radiation area on a moving belt). Even in these cases the volume is relatively small and the radiation intensity is still very high. Obviously any exposure to the primary radiation, the beam itself, presents most extreme hazards.

The primary particles, as a result of their charge and the consequent strong interaction with the electrons of the material through which they pass, have poor penetrating power and can be absorbed by very small amounts of material. Stopping the primary radiation is, therefore, not difficult, but secondary radiation, which may be much more penetrating, is produced in the process.

### 4.2.2 Secondary Radiation

The energy of the individual particles in the secondary radiation is less than that of the particles in the primary radiation, but there may be many more secondary particles and some of them are much more penetrating than are the primary particles.

Electrons, protons and positive ions are created when the beam strikes a target, but the ranges of these particles are very small compared to that of other radiation which is also created. Consequently little attention need be given to these forms of secondary radiation except in the room containing the target.

X-rays, gamma rays, and neutrons are also created when the primary radiation strikes a target. These radiations are very penetrating and are responsible for the large amount of thick shielding which often encloses an accelerator.

Often the secondary radiation is the principal useful output of the machine (for example, the X-rays for radiography and the neutrons for activation analysis). Therefore, the accelerator is designed to have the highest possible secondary radiation intensity. This secondary radiation is confined to as small a volume as is practicable in the particular application of the machine making it an extreme hazard. Not all the secondary radiation can be confined to the volume where it is useful, however. Containing this unwanted secondary radiation is the function of the radiation shielding.

X-rays: X-rays and gamma rays are electromagnetic radiations which differ only in their sources. X-rays originate in the electron field outside the nucleus of the atom and gamma rays originate inside the nucleus. Both types are produced in accelerator primary beam interactions.

X-rays can be produced by the rapid deceleration of fast moving electrons. The slowing down of the electrons causes the emission of X-rays, which are known as "bremsstrahlung" from the German word meaning "braking radiation". Suitable beams of high energy X-rays are usually produced by accelerating electrons and then stopping them in a target of dense material. The energy of X-rays is usually expressed as the maximum or peak energy of the impinging electrons. In a typical X-ray production process the X-rays are emitted in a broad energy spectrum ranging up to the maximum energy of the accelerated electron used. Stopping fast electrons produces a continuous spectrum of X-rays. Any electron accelerator can serve as an X-ray source.

The efficiency of conversion of kinetic energy into bremsstrahlung radiation increases with increasing electron energy and with increasing atomic number of the target material. In a thick tungsten target, for example, a 10 MeV electron converts about 30 percent of its energy into X-rays, whereas a 100 MeV electron converts over 75 percent of its energy (3).

Gamma Rays: Gamma rays are emitted by nuclear interaction of the primary beam with the target material and by naturally occurring and artificially produced radioactive materials. Gamma rays with energies from about 10 keV up to 7 MeV occur in radioactive decay. These rays are produced when a radioactive nucleus gives up its excitation energy and returns to a stable state. Frequently the transition does not proceed directly from an upper state to the stable state, but may go through several energy levels involving intermediate excited states with the radiation of corresponding energies.

The common characteristics and effects of X-rays and gamma rays are:

(1) Ability to penetrate matter.

(2) Ability to ionize, resulting in photographic effects and chemical changes.

(3) Ability to cause nuclear transformations (photo-disintegration) at energies greater than a few MeV.

(4) Ability to cause fluorescence or scintillation.

(5) Biological effects.

(6) Aging effects and radiation damage to materials.

Neutrons: In 1932 Chadwick discovered that the bombardment of beryllium with alpha particles produced a new kind of particle which carried no electric charge, and which was therefore named neutron. He found that its mass was very nearly equal to the mass of the proton. Early experiments with particle accelerators revealed many circumstances in which neutrons were ejected. The process depends on the incident particle (the heavier particles are more effective), its energy (neutrons are more likely to be emitted as the energy of the incident particle increases), and the energy required to remove the neutron from the nucleus (known as the binding energy). Neutron binding energies generally lie between 7 and 15 MeV. Below 7 MeV there are a few reactions which produce neutrons. These low energy reactions are used to produce neutrons from potential-drop accelerators. Useful target materials of low binding energy are deuterium, tritium, lithium and beryllium. Neutrons are also produced by cyclotrons and electron linear accelerators.

In positive-ion accelerators the neutron production occurs directly from the target. In electron accelerators, an intermediate target is usually used to create a bremsstrahlung beam which then strikes a second target from which the neutrons are produced. More detailed information on neutron production reactions is given in references *(3)* and *(4)*.

Neutrons are classed according to their kinetic energy. For convenience, neutron energy ranges have been defined as follows: *(4)*

| | |
|---|---|
| Thermal (room temperature) | 0.025 eV |
| Epi-thermal | 0.025 eV - 1 eV |
| Slow | 1 eV - 1 keV |
| Intermediate | 1 keV - 1 MeV |
| Fast | 1 MeV - 100 MeV |
| Ultrafast | above 100 MeV |

### 4.2.3 Stray Radiation

In addition to the expected radiations from any accelerator, there are other possible sources of radiation which may or may not produce significant levels at a particular installation.

Special circumstances or conditions may exist which cause the production of unpredicted and unwanted radiation. Each type of accelerator, and each specific design, has inherent capabilities for producing stray radiation which are known to the designers, or which may be discovered during operation. In all cases, careful radiation surveys should be made in all occupied areas when a facility is first brought into operation, as well as after any major change in the machine, its mode of operation, or the construction of the facility.

Radiation hazards which exist around particle accelerators may vary according to (1) the type of accelerator, (2) the particles accelerated, (3) the energy of the accelerated particle and (4) the use of the beam. The type and thickness of shielding used around the accelerator may also vary resulting in different levels of radiation outside the shielding of otherwise similar accelerator installations. As a result, it is difficult to predict the levels of radiation in any area of concern without making measurements on the spot. However, it is possible to list the causes of unwanted radiation which may exist. Table 1 lists accelerator types, the particles accelerated, energies of the particles, and the radiations possible in normally occupiable areas for specific uses of the beam.

Radiation surveys should be performed at regular intervals to check the effectiveness of the shielding around the accelerator and irradiation rooms. Survey procedures and detection instruments for this purpose are described in Section 4.7.

Stray radiation may occur due to misalignment, back-streaming, or dark current. If parts of the accelerator are misaligned, a portion of the internal beam may strike the interior of the accelerator and cause stray radiation from an unusual area of the machine. This can be an especially serious hazard under abnormal operating conditions.

The external beam may pass through focussing and bending magnets, and in case of magnet failure or incorrect adjustment, the beam may strike something other than the intended target, producing unexpected amounts and types of secondary radiation.

These sources of stray radiation may create a hazard even when the useful beam is at zero intensity and the instruments which monitor the useful radiation show small or negligible radiation in the normal radiation areas.

Back-streaming usually occurs in potential-drop accelerators. The beam of charged particles that is accelerated from the ion source to the target causes a stream of particles of opposite charge to be released and accelerated in the opposite direction.

Unintentional or uncontrolled processes may create electrons or ions in an accelerator even when the normal source is turned off. This unintended beam, called "dark current," takes its name by analogy with the current observed through a photo tube in the absence of light. Among the mechanisms of unintended electron and ion production are field emission resulting from the high voltage gradients which exist in the accelerating strucuture, sparks, and ions produced by cosmic rays or radioactive decay. Although the dark current is ordinarily very small, it may be continuous. The electron or ion source, on the other hand, is often pulsed at a low duty cycle. Thus the average dark current may approach or even exceed the normal average beam current.

Table 1. Radiation of Possible Concern in Occupiable Areas of Particle Accelerator Facilities

| Accelerator | Particles Accelerated | Beam Energy MeV | Purpose of Operation | Radiation of Possible Concern in Occupiable Areas |
|---|---|---|---|---|
| Potential-drop | Protons<br>Deuterons<br>Alpha Particles | 1-10<br>1-10<br>2-20 | Research<br>Neutron Production<br>Neutron Radiography<br>Activation Analysis | Fast Neutrons<br>Thermal Neutrons<br>Gamma Rays |
| | Electrons | 1-10 | Processing<br>Radiography<br>Therapy | Electrons<br>X-rays |
| Electron Linear | Electrons | 1-10 | Processing<br>Radiography<br>Therapy | Electrons<br>X-rays |
| | Electrons | $>10$ | Research<br>Neutron Production<br>Neutron Radiography<br>Activation Analysis | Electrons<br>X-rays<br>Fast Neutrons<br>Thermal Neutrons<br>Gamma Rays |
| Cyclotron | Protons<br>Deuterons<br>Alpha Particles | 15-50<br>7.5-24<br>15-50 | Research<br>Isotope Production<br>Neutron Production<br>Neutron Radiography<br>Activation Analysis | Fast Neutrons<br>Thermal Neutrons<br>Gamma Rays |
| Betatron | Electrons | 1-50 | Radiography<br>Therapy | Electrons<br>X-rays |

## 4.3 Induced Radioactivity in Materials

### 4.3.1 Activation of Targets and Accelerator

The target which is being intentionally irradiated will usually become radioactive. Any other material which the beam strikes or which is exposed to intense secondary radiation may also become radioactive. In both electron and positive ion accelerators the beam usually strikes other objects such as vacuum chamber walls and electrode supports. Radiation from these sources will not normally be a personnel hazard until the machine is turned off and personnel enter irradiation rooms and the accelerator room for maintenance, target changes, or routine adjustments. A survey of these areas should be made to evaluate the radiation hazard before or as they are being entered.

Activation of cooling water and other cooling media in targets may be a problem. If a recirculating system is used, a portion of the system may expose personnel in areas which are normally occupiable during accelerator operation. Even though the activated water is no hazard during normal operation, the residual activity present during maintenance work on the water system may be hazardous for a time after shutting down the accelerator. The activated cooling media should be monitored and dealt with according to the levels of activity involved. Shielding may be required around circulating pumps, heat exchangers and holding tanks. If irradiated water is discharged into the sewer system, it may be necessary to hold it in adequately shielded tanks until it decays to such a level that it may be disposed of without exceeding local restrictions.

The induced radioactivity may cover a wide range in intensity and in half-life and come from many radioactive isotopes. The many different materials used in and around an accelerator which can be bombarded by the positive ions, neutrons and gamma rays can lead to a spread in half-lives nearly as great as in the fission-product spectrum from a nuclear reactor, with a similar composite decay curve. Highest intensities of induced activities are produced by accelerators which have high neutron yields, such as the cyclotron. The intensity following shutdown under normal conditions may be sufficient to overexpose a person in a matter of minutes, as indicated in Section 3.4.3. Whenever possible, repairs and other maintenance tasks should be postponed until after an overnight or weekend shutdown, when the safe time for a daily dose may be extended to several hours.

Studies of the activation of each individual accelerator should be made at least annually to determine levels of radiation intensity and to plot activation decay curves for several locations about the accelerator. The studies should be made after each major beam current or energy change. Results obtained can be helpful in planning maintenance. Using these results, the radiation safety officer can plan working times for urgent repairs in the various fields. After several years, long-lived activities may build up which are not appreciably affected by delays of hours or days after shut-down. This makes maintenance increasingly difficult as operating time accumulates. In order to remedy this situation, the most active parts should be removed or shielded.

### 4.3.2 Airborne Radioactive Materials

Air in the accelerator room and irradiation rooms may become radioactive in the following ways:

(1) If the beam is allowed to pass through air, the elements in the air will become radioactive. The radiation intensity produced depends on the beam energy and intensity. These activities, although short-lived, are potentially hazardous when they get into the body.

(2) Radioactive gases produced internally in the targets may escape into the target area or accelerator room, as the result of a containment failure.

(3) Contamination may be present in particulate or dust form. The contaminating materials may be the result of a ruptured powder target or flaking off of activated surface layers of material, in the area which has been irradiated.

In order to control these hazards, a ventilation system, separate from the building ventilation system, should be provided in all hazardous areas. It should exhaust outside the building and away from the air intake for the building ventilation. The ventilation system should be designed so that the irradiation rooms and accelerator rooms are at a lower pressure than other parts of the building. Several flow rates may be desirable, so that the rate of flow can be increased during periods of high beam intensity, or before the area is entered.

If limited ventilation is provided in hazardous areas, and the concentration of radioactive gases and ozone build up during an irradiation, time should be allowed for the activity to fall to permissible levels, before entry to the hazardous area. The level of radiation should be checked, following a period when the beam is on, and prior to allowing personnel to enter the area to perform routine maintenance, target changes, or adjustments.

In any event, it is desirable to monitor the concentration of airborne activity in the hazardous areas when the beam is on and when it is off. A sample calculation for air activation by an electron beam, passing through air, is shown in Appendix B. Positive-ion beams can also create radioactivity in the air, but these beams are seldom used in a manner which involves long paths in air.

Swipes of the floor should be taken upon entering areas where loose radioactive dust may exist. If loose contamination goes undetected, it may be tracked through the building. The activated dust may become airborne and create biological hazards from inhalation and ingestion. Dust in the suspected rooms should be collected with a vacuum cleaner used only for this purpose. The material collected in the vacuum cleaner should be disposed of as radioactive waste, in a prescribed manner. There are commercial firms which provide radioactive waste disposal services, including supplying waste containers and pickup for disposal, at predetermined intervals.

### 4.3.3 Handling Activated Materials

The radiation hazards of handling activated materials may be classified into the following two groups:

(1) The hazard of radiation emitted by radioactive material external to the body.

(2) The hazard of radiation emitted by contaminating radioactive material which is in contact with the skin or clothing, or ingested or inhaled. Before handling or working with or around any activated materials, a health physicist or other informed and responsible person should be consulted to recommend safe handling procedures.

Any material which is suspected of radioactivity, should be monitored to determine the level and type of radiation present. Additional steps should be taken to determine whether items to be handled have loose activity on them. Whenever radioactive materials are to be handled, personnel should wear plastic or surgical gloves and wash their hands thoroughly after the work, to avoid spreading or ingesting any contaminants that might remain on them.

Radioactive materials, which are powdered and tend to flake, should be handled in hoods or glove boxes in which adequate ventilation is provided. The ventilation should exhaust outside the building and include a high efficiency filter.

Transfer of loose, powdered, or alpha-emitting materials should be made in sealed containers or plastic bags. Tools and equipment used around an accelerator, where possible loose activity may exist, should be considered radioactive until proven otherwise.

### 4.3.4 Storage of Activated Materials

Shielded storage areas or storage containers should be provided for bombarded targets and other radioactive items. It may be desirable to store small radioactive components of the accelerator to lower the background radiation during maintenance operations on the accelerator. Any nuts, bolts, and other small objects, removed during maintenance operations on the accelerator, should be placed in marked containers. These objects may be certified for reuse, if the level of induced activity does not create a hazard. Any radioactive components, which must be left exposed, should be clearly labeled to indicate the severity of the hazard.

### 4.3.5 Machining Activated Materials

Machining radioactive materials or components of the accelerator, which have become radioactive, should be done in a controlled environment where any radioactive dust or chips can be confined and contained. Protective clothing should be worn during such machining operations. Work on the accelerator proper will also necessitate protective clothing when making contact with the interior surfaces of the accelerator vacuum tank. Whenever possible, specific areas and machine tools should be set aside for working on radioactive materials. Once a machine has been used for machining radioactive materials, it is extremely difficult and expensive to decontaminate it completely. Therefore, it is obviously desirable to limit the number of machine tools and the shop area that might become contaminated.

## 4.4 Contamination of Accelerator Facilities

### 4.4.1 Vacuum Pump Exhaust

Exhaust from accelerator vacuum pumps may contain toxic and radioactive gases. The radioactive gases may be absorbed in the vacuum system as the result of leakage from targets or from target failure. The exhaust from the pumps should be vented outside the building and away from building ventilation system intakes.

### 4.4.2 Vacuum System Maintenance

Maintenance of vacuum systems and vacuum system components may be hazardous. The vacuum system, as well as pumps and pump oils, may become contaminated with radioactive materials. The materials may be from targets which vaporized or burst during bombardment. Special precautions should be followed when opening a vacuum system for decontamination or service, as material may be knocked loose and become airborne or scattered about on the floor. The contaminated parts to be serviced should be removed in plastic bags. All service work, or repairs, on components should be performed in hoods or well-ventilated areas.

### 4.4.3 Tritium

Particle accelerators may be used for the production of intense beams of neutrons by means of the deuterium-tritium reaction. During bombardment by deuterium, tritium gas is released from the target. This tritium outgassing is a major cause of tritium contamination within the beam tube assembly, vacuum system, and exhaust system.

Tritium is the only radioactive isotope of hydrogen. It is commonly present as tritium gas (HT or $T_2$), as tritium oxide (HTO or $T_2O$), or a mixture of both the gas and oxide. Tritium emits an 18-keV beta particle, and has a half-life of about 12 years. The range of this radiation is about 0.6 milligrams per square centimeter, which is less than the thickness of the outer layer of skin on the body *(5)*. Thus, it is no external radiation hazard. However, within the body, there is no protection to living tissues. With tritium in the body fluids, the entire energy of the beta particles may be absorbed within a single cell nucleus. Although the half-life of tritium is approximately 12 years, tritium is eliminated by the body with an effective half-life of approximately 12 days *(5)*.

When a person is exposed to an atmosphere containing HTO, the HTO entering the body through the total skin area is approximately equal to that entering through the lungs *(6)*. Once tritium is absorbed by the body, the isotope becomes uniformly distributed throughout the body fluids within approximately 90 minutes *(7)*. Tritium gas, in the elemental form, does not present as significant an internal hazard as tritium oxide, since elemental tritium is absorbed into the body at a much slower rate. Under the worst conditions a lethal quantity of HTO or $T_2O$ can be introduced into the body of a man in a few seconds of exposure, or in the time required to take one breath in an atmosphere saturated with $T_2O$ vapor *(7)*.

Tritium is not produced in significant amounts by accelerators. It is present only when brought into the laboratory as a material absorbed in a tritium target or otherwise. When tritium is bombarded by positive ions, the following hazards exist:

(1) Large quantities of tritium buildup in electronic "ion getter" vacuum pumps. These pumps should not be serviced unless proper facilities and trained personnel are available. Potentially lethal amounts of tritium may be present on the inner surfaces of the pumps.

(2) Tritium accumulates in various mechanical and diffusion vacuum pumps. During vacuum system operation significant quantities of tritium may pass through the diffusion pump. Some tritium will be trapped in the oil. No attempt to service these pumps should be made unless proper facilities and trained personnel are available.

(3) Tritium contamination may be present on certain components of the accelerator system. The tritium can become a hazard when the vacuum system is opened to the atmosphere, as for target changes, maintenance, or through leakage or breakage. Target replacement procedures and other manufacturer recommendations should be closely observed. The vacuum system should be opened by personnel well versed in the hazards and proper techniques to be used.

(4) Tritium will be released to the environment through pump exhaust. Mechanical pumps, used in conjunction with both diffusion pumps and ion-getter pumps, should be vented outside the building. The exhaust should be monitored to ensure that tritium discharge limits for the specific area are not exceeded.

(5) Used oil and targets should be contained in material through which tritium will not readily diffuse (glass is not recommended). Ventilation and temperature control should be provided in the area where tritium waste is held pending disposal as radioactive waste.

(6) The considerations regarding unused tritium targets are very much the same as in waste holdup. A slightly greater potential hazard exists in this situation however, due to larger quantities of tritium. Control of ventilation and temperature in the storage area must be considered. Unused targets should be kept in the container in which they were supplied. Each container should be placed in a ventilated area. Unused targets should not be combined in one large container, as the buildup over several weeks may exceed the maximum permissible concentration.

(7) There are difficulties encountered in the detection of tritium. Nuclear instrumentation capable of accurate tritium detection is commercially available. However, sensitivity, discrimination between tritium and other gases, and calibration of these devices, present problems which must be clearly understood by the user.

Neutron generator instruction manuals should be referred to for specific operating instructions. Additional information and references on the subject of tritium hazards, may be found in References (5) and (8).

### 4.5 Shielding

Shielding is normally provided around particle accelerators at the time the machine is installed. The shielding, which may have been adequate at the time of installation, may at a later date be inadequate for one of several reasons:

(1) Cracks or other openings may occur.

(2) The machine may be modified to produce higher beam energies or intensities, or to accelerate different particles.

(3) The shielding configuration may be changed.

(4) The shield material, or structure, may deteriorate.

Surveys of the area around the shielding should be made periodically. If a defect in the shielding does exist, the background radiation in the immediate area may increase. Steps should be taken to locate the defect and make the necessary corrections. If the defect is difficult to locate, a map of the distribution of radiation intensity, showing contours of equal intensity, may be useful.

The material chosen for shielding in an accelerator facility, usually depends on the dominant radiation from the accelerator and on cost, bulk, and convenience factors. Heavy materials, such as lead and iron or steel, are sometimes used for specific localized shielding, such as containers for radioactive materials and shields around accelerator targets. Ordinary concrete is the most common material for general shielding. Concrete contains a mixture of both light and medium elements, and consequently, is effective in several absorption processes. It is usually much cheaper than other materials for comparable results.

Heavy materials, such as scrap iron, may be added to concrete to increase its effectiveness, or heavy concretes with densities up to nearly 250 pounds per cubic foot, can be made by using special types of aggregate. Since heavy concrete costs more than ordinary concrete for equal attenuation, this kind of shielding is used only where the saving in space justifies the higher cost.

There are many processes by which attenuation in the shielding takes place, because many reactions can occur between each type of radiation and the materials in the shielding. Usually one type of radiation will be present in much higher intensity than others, or be much more penetrating than others. Shielding, which is adequate for the most important component, usually reduces other radiation to negligible levels. However, if the operation of the accelerator is changed, for example by changing targets, the secondary radiation may be different enough to require more shielding.

The absorption of the primary beam particles is generally accomplished by small amounts of material. Each type of charged particle, at a specific energy, has a definite range in a given material. Metals, especially heavy metals, are better absorbers of charged particles than light materials, such as concrete or water. At energies below 100 MeV, a few inches of metal are sufficient to stop all the primary beam particles.

Some of the secondary radiations, notably gamma rays and neutrons, are very penetrating and necessitate much larger amounts of shielding. The intensity and energy of neutrons or gamma rays depends very strongly on the type and energy of the primary beam, and on the elements in the target. Positive particles, especially deuterons, can produce a high neutron flux and these neutrons can, in turn, produce gamma rays. In general, all electron beams create X-rays. The intensity of the X-rays increases rapidly with increasing energy and with increasing atomic number of the target material. Above 10 to 15 MeV, the X-rays can also eject neutrons from the shielding.

Most, but not all, of the secondary radiation has the same general direction as the primary beam. Therefore, the shielding required in the forward direction is usually somewhat thicker than that required in other directions. Although many different reactions between the secondaries and shielding material are possible, none of them are as effective as the processes by which charged particles are absorbed.

Heavy metals are most effective in absorbing gamma rays, but not usually satisfactory for neutrons. Light elements are needed to moderate neutrons to the very low energies where capture processes occur. Sometimes composite shields containing metals, hydrogenous material, such as water or paraffin, and non-radiative capture elements, such as boron, are used. Concrete has enough diverse elements to serve all these purposes at minimum cost and is ordinarily preferred.

The half-value thickness for any material is the thickness necessary to reduce the intensity of a specific type of radiation to half its initial value. The half-value thickness in ordinary concrete for neutrons and for gamma rays, at the energies appropriate to small accelerators, are about 10 centimeters and 15 centimeters respectively. Exact values of course depend on the specific energy spectrum and concrete composition in a particular situation.

A narrow beam of high-energy X-rays will create a particular intensity of ionization in a gas-filled ionization chamber placed in the beam. If a layer of absorbing material several centimeters thick is placed between the beam and the chamber, the ionization may increase to several times its previous intensity. Thus, the presence of a moderate amount of shielding appears to increase the radiation. This increase is because the incident X-rays produce energetic secondary electrons. These secondary electrons, in turn, create X-rays by the bremsstrahlung process, which adds to the primary X-ray intensity. This sequence of interactions may occur several times. By this process the initial high-energy radiation, which produces a certain amount of ionization in the detection chamber, is degraded into a larger amount of lower-energy radiation with much larger total ionizing ability.

This buildup increases as the original X-ray beam penetrates into the absorber. It depends on the particular beam and absorber geometry, the X-ray energy spectrum, and the absorber in the particular situation. The general result for accelerators of moderate energy is that some added shielding, beyond that which would be calculated on the basis of monoenergetic narrow-beam absorption coefficients, is required. This amount may be as much as two or three half-value layers in extreme cases.

Certain special shielding situations are discussed in the following paragraphs.

### 4.5.1 Ventilation Ducts and Shielding Walls Penetrations

Ventilation ducts and penetrations through shielding walls may be a potential radiation hazard. Surveys should be conducted to determine the levels of radiation that exist outside of the shielding in the area of penetration.

If ventilation ducts are large enough for a man to crawl through, an additional hazard may exist. Inspection covers and doors, outside the shielding, should be interlocked to avoid inadvertent opening of the duct during operation. This precaution may prevent the accidental exposure of a person doing a routine inspection of the system or the escape of toxic gases into the building.

### 4.5.2 Changes in Shielding Effectiveness

Even though shields may be satisfactory when installed, they may deteriorate, either suddenly or gradually. It is necessary, therefore, to conduct routine radiation surveys outside the shielding.

Shielding around accelerators is not always cast into place, but may be built up of separate blocks. All vertical joints should be staggered to reduce leakage of radiation. Gravity is usually sufficient to keep horizontal cracks closed, but joints should not be placed in the plane of the primary beam.

### 4.5.3 Shielding Against Residual Activity

Usually the only radiation which will be present after the accelerator has been turned off are beta and gamma rays. In some cases, however, alpha particle contamination may be present.

Materials of low atomic number are the most effective beta-ray shielding. X-ray production (bremsstrahlung) due to stopping of the beta particles is lowest with low atomic number material, such as plexiglass. A thickness of one-eigth of an inch will stop beta particles up to 1 MeV energy, while one inch will stop up to 4 MeV beta particles. Where very large fluxes of beta particles are involved, the bremsstrahlung can be quite important and further shielding with heavy material, such as lead, may be required to reduce this more penetrating radiation to a satisfactory level. Figure 10 shows the range of monoenergetic beta particles as a function of energy in various materials. The chart may be useful for determining adequate shield thicknesses for radioactive materials emitting beta particles of a known energy.

Material of high atomic number is most effective for gamma ray shielding. Figure 11 gives the amount of material to reduce gamma rays of known energy and for narrow beam conditions (as described in the following section) to one tenth of their unshielded intensity. The buildup effect discussed in Section 4.5 is not included in these curves.

Alpha particles can be stopped by very thin absorbing materials, such as a few sheets of paper or thin metal. Therefore, alpha radiation is not considered an external exposure problem; the hazard is that of ingestion or inhalation. All alpha-emitting materials should be contained in plastic bags or sealed paper cartons. Any such containment will usually be sufficient to absorb the energy of the alpha particles.

### 4.5.4 Beam Stops

The primary purpose of beam stops and plugs is to prevent the beam from being accidentally directed into any occupied irradiation rooms, while the accelerator is operating for other purposes. The beam stop is opened only when its particular target room is to be used. Wherever possible, a person entering a target room should be able to see the beam stop. Where this is not possible, a mechanical indicator operating with the stop, should be used.

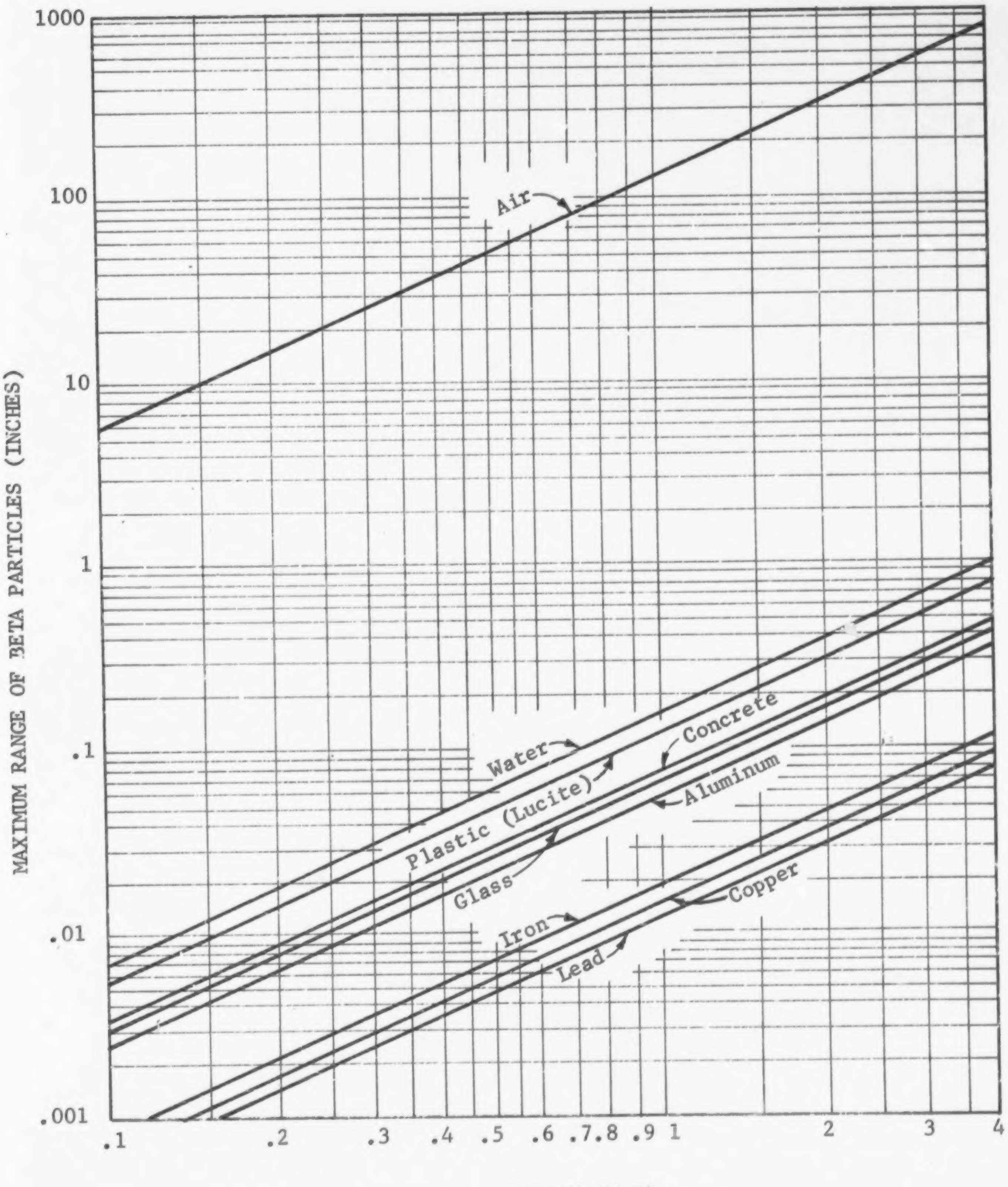

Figure 10. Penetration Ability of Beta Radiation in Varous Materials (9)

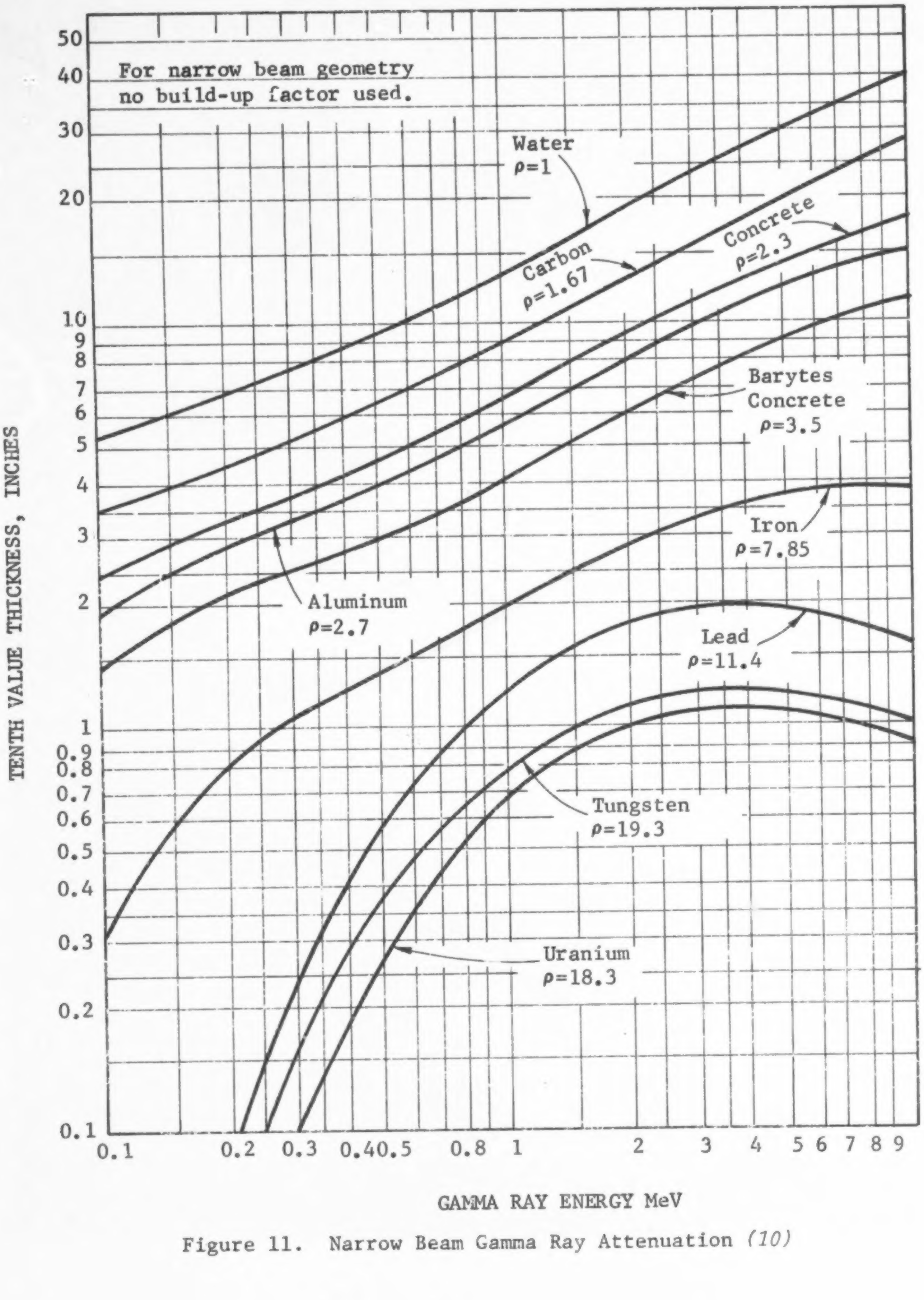

Figure 11. Narrow Beam Gamma Ray Attenuation *(10)*

### 4.5.5 Skyshine

Upward-directed radiation which is scattered back toward the surface of the earth by collision with nuclei in the air is known as "skyshine." Neutrons in an energy range from 1 to 10 MeV prove to be the significant radiation component of skyshine for most accelerators *(11)*.

Skyshine around accelerators is a hazard which may go undetected. The extent to which radiation emitted through the roof of the shielded area or through an unshielded roof will scatter back to ground level is sometimes not recognized. Some accelerators may have little roof shielding because of the absence of occupiable areas overhead. Wall shielding, in the absence of roof shielding, will reduce radiation levels near shield wall, but the radiation levels further away may be high because of the skyshine. It should not be assumed that if radiation dose rates are all within acceptable limits close to the shield of an accelerator, that they are always lower further away. A survey made of the area close to the shield wall, as well as further away, may indicate the need for additional roof shielding.

### 4.5.6 Typical Shielding for Various Accelerators

Table 2 is a summary of shielding thicknesses of ordinary concrete required around typical accelerator facilities. This information is to be considered only illustrative and is not to be used for design purposes.

## 4.6 Safety Interlocks and Warning Devices

### 4.6.1 Interlock Systems

Interlocks are electrical circuits which act to turn off or hold off electrical power if a hazardous situation exists. An accelerator usually has many interlocked subsystems. Each interlock is intended to furnish protection to personnel or equipment in the event of a specific malfunction or improper operating condition.

Each of the individual interlock functions acts to open or close a pair of electrical contacts, either directly or through a relay. Many pairs of contacts in series must be closed to provide control power for the "beam on" switch. Often subsystems have smaller series chains, which culminate in a single pair of contacts in the main interlock chain. There is a great deal of variation in the interlocking arrangements to be found in different accelerators. This is due to the inherent differences among accelerators, specific space or component limitations, and differences in design philosophy, cost factors, and users' requirements. Ideally, the interlock system should be "fail-safe" in the sense that defects or component failures, in the chain itself, will prevent operation of the accelerator.

Table 2. Typical Radiation Shielding

| Accelerator Type | Internal Beam | Beam Energy | Average Current |
|---|---|---|---|
| Potential-Drop | Deuteron | 0.1 MeV | 100 μa |
| " " | Deuteron | 0.4 MeV | 100 μa |
| " " | Deuteron | 0.5 MeV | 1000 μa |
| " " | p, d, α | 1 MeV | 1000 μa |
| " " | p, d, α | 2 MeV | 750 μa |
| " " | p, d, α | 3 MeV | 750 μa |
| " " | Electron | 1 MeV | 1700 μa |
| " " | Electron | 2 MeV | 1000 μa |
| " " | Electron | 3 MeV | 1000 μa |
| " " | Electron | 6 MeV | 100 μa |
| Linac | Electron | 6 MeV | 10 μa |
| " | Electron | 8 MeV | 40 μa |
| " | Electron | 20 MeV | 360 μa |
| Cyclotron | Proton | 15 MeV | 100 μa |
| Betatron | Electron | 20 MeV | --- |
| " | Electron | 20 MeV | --- |
| " | Electron | 30 MeV | --- |
| " | Electron | 30 MeV | --- |

(A) Assuming approximately 25 feet from target to occupied area.
(B) Top Shielding assuming areas above the accelerator are occupied and distance from the target to the occupied area is the same as the geometry to the side.
(C) Base Shielding not required if accelerator is mounted on the ground floor.
(D) This information is to be considered only illustrative and is not to be used for design purposes.

for Particle Accelerators (D)

|  | Radiation To Shield | APPROXIMATE SHIELDING REQUIREMENTS (A) (inches of ordinary concrete, 147 lb/ft$^3$) |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
|  |  | Forward | Rear | Side | Top(B) | Base | Ref. |
|  | 14 MeV Neutrons | 16 | 16 | 16 | 16 | (C) | *4,12* |
|  | 14 MeV Neutrons | 30 | 30 | 30 | 30 | (C) | *4,12* |
|  | 14 MeV Neutrons | 58 | 58 | 58 | 58 | (C) | *4,12* |
|  | Stray X-rays (E) | Target-dependent | 12 | 8 | 8 | 8 | *13* |
|  | Stray X-rays (E) | Target-dependent | 18 | 12 | 12 | 8 | *13* |
|  | Stray X-rays (E) | Target-dependent | 36 | 30 | 30 | 8 | *13* |
|  | X-rays | 30 | 30 | 30 | 30 | (C) | *13,14,15* |
|  | X-rays | 42 | 40 | 40 | 40 | (C) | *13,14,15* |
|  | X-rays | 57 | 40 | 50 | 50 | (C) | *13,14,15* |
|  | X-rays | 74 | 52 | 63 | 63 | (C) | *15,16* |
|  | X-rays | 60 | 38 | 50 | 50 | (C) | *15,16* |
|  | X-rays | 87 | 60 | 72 | 72 | (C) | *15,16* |
|  | X-rays | 131 | 95 | 95 | 95 | (C) | *15,16* |
|  | Neutrons | 48 | 48 | 48 | 48 | (C) |  |
|  | X-rays (F) | 82 | 27 | 47 | 47 | (C) | *16,17,18* |
|  | X-rays (G) | 100 | 45 | 65 | 65 | (C) | *16,17,18* |
|  | X-rays (F) | 85 | 28 | 50 | 50 | (C) | *16,17,18* |
|  | X-rays (G) | 105 | 46 | 67 | 67 | (C) | *16,17,18* |

(E) Neglecting Neutrons
(F) $10^2$ R/min @ 3 ft. from target
(G) $10^3$ R/min @ 3 ft. from target

The most important part of an accelerator interlock system is that which deals with radiation hazards. The radiation interlock system has two general functions: to prevent access to areas in which unsafe radiation levels are being produced by the accelerator; and to prevent operation of the accelerator if such operation will produce an unsafe radiation level in any occupied area.

Targets or experiments to be irradiated are usually located in shielded rooms. The beam may enter the room through beam pipe which penetrates a shielding wall between the accelerator vault and the target room, or the target may be located in a room with the accelerator. Access to the target room is either through a maze or through a doorway, which is blocked during irradiation by a shielding door. In either case, it should be necessary for personnel entering the room to open a door which shuts off the accelerator.

In nearly all accelerators, a key-operated switch is incorporated in the beam controls. The key to this switch should be required to unlock the door or gate leading to the target area. Thus the beam must be turned off and the key removed from the switch, before anyone can enter the area of most extreme hazard. In accelerator facilities where there are two or more entrances to the target area or more than one irradiation room, more elaborate key-switch circuits are often used. Also, additional switches, which are closed only when doors, gates, shielding plugs, and shielding doors are in a safe condition, may be used in series with the key switch.

Accelerator personnel must not depend on a door interlock to turn off the beam. If the door interlock fails, a serious radiation exposure is almost certain to occur. The switch on the control console should always be placed in the "off" position before entering the radiation area. Similarly, the accelerator should never be turned on from any place but the control console.

One or more disabling switches should be installed in target areas and experiment rooms, so persons in those areas can turn off the accelerator or prevent the beam being turned on, in the event that they are trapped when someone else attempts to turn on the beam.

The control circuits should produce a warning by light or sound, or both, for some period after the irradiation rooms are closed and before the beam can be turned on, to allow anyone trapped in a room to reach the disabling switch. The irradiation room door should be operable from the inside even after power failure. The door handle should open the accelerator interlock, whether or not it opens the door.

Lockout procedures for hazardous (may more descriptively be called "search and evict" procedures) areas should be adopted and adhered to. A walk-through system which forces inspection of hazardous areas may be necessary. Such a system should incorporate electrical push buttons at various points throughout hazardous areas, with accelerator start-up impossible until all buttons are sequentially depressed. A person performing the lockout procedure is thus required to walk through the hazardous areas and perform a visual inspection. In smaller installations or in small irradiation rooms, a single button at the far end of the room may be sufficient.

Radiation-detection instruments should be installed to monitor the radiation levels in various areas, including the control room and other rooms normally occupied when the beam is on. Monitors may be installed in target areas and experimental areas which are not occupied but where the radiation level is an important indicator of accelerator performance. Sometimes these radiation intensities are recorded automatically. The instruments should turn off the beam and give warning, if the permissible radiation level has been exceeded. These instruments should be adjusted to the proper levels and tested periodically.

A part of the interlock system deals with extreme electrical hazards to personnel, particularly high-voltage DC power supplies. Switches on the access doors to high-voltage compartments should interrupt the input voltage to the compartment when the doors are opened, and should discharge capacitor banks. In general, any electrical hazard which has a protective enclosure should have interlock switches installed to open the power circuit if the enclosure is opened.

It should always be remembered that these interlocks seldom act directly to remove the hazard, but rather act through intermediate relay circuits. Even though the interlock switch in a door frame is visibly in the open or safe position, the other parts of the interlock circuit may fail to operate correctly, and the hazard may still exist. Also, relays or switches may fail, or become misaligned, so that these interlocks are not completely dependable. It should never be assumed that the interlocks have removed the hazard.

A complete interlock chain includes many pairs of contacts, arranged in various main and subsidiary sequences; some of these are "power-on" sequences, but some may be "power-off" sequences. The complexity of an interlock chain can lead to misunderstanding on the part of inexperienced operators and technicians. Therefore, complete and accurate circuit diagrams of the entire interlock system are essential. These drawings should be readily available to the operators and to the technicians who are responsible for maintenance of the accelerator, and such persons should become familiar with the circuits.

Faulty diagnosis or improper repair can create a condition in which the interlock chain appears to be operating correctly, but important elements of the chain have been bypassed or overridden. Any repairs made to the interlock circuits, especially those involving modifications or substitutions of components, should be carefully recorded in log books and on the circuit diagrams.

It is frequently a convenience and a means of conserving operating time to circumvent a troublesome interlock component (such as a sticking relay or an erratic contact susceptible to vibration) by installing a jumper or bypass across accessible terminals in the control room, rather than shutting down the accelerator until a replacement for the troublesome component can be obtained and installed. Experienced operators may be able to do this and monitor the bypassed interlock function personally, with adequate safety and with considerable benefit to the work of the laboratory. However, if the operator became careless and failed to record the change, or failed to make it conspicuously obvious to all others concerned, an extremely hazardous condition could result. Any temporary change in the interlock system should be made unmistakably evident to every person who could be endangered by the change.

Where fail-safe operation of equipment cannot be otherwise assured, a duplicate system of interlocks should be used. In this case, mechanical-electrical interlock systems for doors, etc., should be carried through in duplicate, with wiring, contacts, and relays, located so as to make simultaneous failure of both circuits extremely unlikely. The hazard of someone disabling the system (for example, by placing a concrete block on a cable) is avoided by using widely separated cables in the two systems. An important requirement of a duplicate system, however, is that failure of either of the two circuits should be conspicuously signaled, so that it can be corrected. The system is safe only when both circuits say safe; it is hazardous when either says that; and it is broken when they disagree. Whatever type of system is used, a frequent check of its proper operation is essential.

Another type of interlock which may be used with an accelerator is one which detects a hazardous concentration of explosive or flammable gas such as hydrogen, and turns off equipment which could ignite the gas.

### 4.6.2 Warning Devices

In addition to interlocks to prevent inadvertent entry into hazardous areas during accelerator operation, warning devices should be utilized to inform people of the machine status. Lights, signs and audible devices can be used.

(1) Status Lights. The location of status lights is important. They should be located in the accelerator vault, irradiation rooms, corridors leading to the irradiation rooms, and on the control console. The status lights should indicate magnet status, beam status, and any other condition considered important for the safety of operating personnel. Regular checks should be made to make sure the light bulbs have not burned out.

(2) Signs. Signs should be used to mark areas where hazardous radiation levels could exist. Appropriate radiation surveys should be

made and occupancy times established. Definitions of "radiation area" and "high radiation area" have been established by the USAEC in connection with radioactive source material *(19)*. These definitions can also be applied to accelerator facilities. A radiation area means any area, accessible to personnel, in which there exists radiation at such levels that a major portion of the body could receive in any one hour a dose in excess of 5 millirem, or in any 5 consecutive days a dose in excess of 100 millirem. The area should be designated as a restricted area and the fact be shown by properly worded and posted signs. A high radiation area means any area, accessible to personnel, in which there exists radiation at such levels that a major portion of the body could receive in any one hour a dose in excess of 100 millirem. The area should be designated as a restricted area and ropes or fences should be used in addition to radiation signs to clearly mark the area.

Because of the frequent changes in radiation level and beam usage in experimental areas, temporary signs and barriers which are readily movable should be available. They should be distinctive in appearance and readily recognizable as warning devices.

(3) Audible Devices. Horns or other audible devices should be used where practical to indicate that the beam is on or is about to come on. If the audible device must be on for long periods, it should make an intermittent tone which is low enough not to distract people working in the area. If the device is loud it will probably be disconnected or modified to make it inaudible. A public address system announcement of impending turn-on can be used in addition to an audible warning signal.

## 4.7 Instrumentation and Monitoring

### 4.7.1 Types of Instruments

The detection instruments which may be used for accelerator radiation surveys are described in this section. The descriptions are intended to give the reader an idea of the types of instruments available. Since the characteristics of each type of instrument may vary from one manufacturer to another, the manufacturers should be consulted for more detailed operating characteristics and recommendations. Pocket dosimeters, using quartz-fibre electrometers, pocket ionization chambers, and film badges useful for personnel monitoring, are included.

In selecting the best instrument for the measurement of radiation for particular dosimetry problem, the convenience of operation, portability reliability, economy, type of radiation, energy, dose rate dependence of the instrument should be considered. Each monitoring job has its own individual set of considerations. It is necessary to know the characteristics and limitations of any survey instrument or pocket dosimeter in order to use it intelligently.

It should be recognized that all instruments are limited to measuring certain types of radiation within a fixed range of energies, and that for other types of radiation or at certain energies of radiation, their readings may not only be useless but often misleading. It is extremely important that survey and monitoring instruments be properly maintained and calibrated, and sensitive to those radiations being monitored.

The detection of ionizing radiation depends usually upon one of the following observable effects of its passage through matter:

(1) Electrical conduction caused by ionization, either by the incident radiation or by secondary particles produced through interaction of the radiation within the instrument.

(2) Fluorescence of selected materials from the decay of short-lived metastable states excited in certain molecules by their interaction with the incident radiation or its secondaries.

(3) Production of developable grains in photographic emulsions.

The most widely used and most generally accepted method is measuring the electrical current resulting from ionization of a gas exposed to radiation. The ionization chamber, the proportional counter and the Geiger Mueller counter (G-M counter), in their various forms, depend upon this principle.

Scintillation counters depend upon the observation of fluorescence by photosensitive devices. Photomultiplier tubes used in these instruments must have adequate magnetic shielding for use around accelerators where magnets are common. Although their development has been slow, there will probably be an increase in the use of scintillation-type survey instruments.

Photographic emulsions on film are widely used for radiation monitoring of personnel. This technique was probably the first used in an attempt to evaluate radiation dose quantitatively. Films are widely used in film badges to monitor personnel for exposure to beta, gamma, and X-rays, as well as neutrons, in which case nuclear track films are used.

### 4.7.2 Radiation Surveys

Survey data should be accumulated during installation tests and during the first routine operations, since the two may be widely different. Routine operation of an accelerator should not begin until a complete radiation survey of the installation has been made. The survey should be directed toward measuring the distribution and magnitude of the following:

(1) Exposure rates in all occupied areas when the beam is on.

(2) Skyshine.

(3) Production of toxic gases during irradiation.

(4) Residual radioactivity in the radiation room and accelerator room when the beam is off. Unless extensive testing time was taken, residual activity should be extremely low prior to routine operation. After routine operation frequent measurements may be necessary as the induced radioactivity builds up.

(5) Residual radioactivity in targets.

Surveys should be made frequently where radiation hazards are suspected, and especially in those areas where accidents or emergency conditions have occurred. Surveys should also be conducted when experiments require unusual source or target handling. Survey frequency should be determined by the use of the area and the cycles of operation.

After initial radiation surveys of an accelerator installation have been made, occupied or occupiable areas should be classified as described below:

(1) Areas in which radiation may be present but is of such an insignificant level that the areas are open to the public.

(2) Areas where unrestricted occupancy by radiation workers may be permitted.

(3) Areas where limited occupancy may be permitted for operational reasons. Personnel monitoring and appropriate warning signs as mentioned in Section 4.6.2 are required in such areas.

(4) Areas where supplementary shielding or other modifications are needed in order to permit regular unrestricted occupancy.

The measurements taken during a survey should be recorded for future reference. Recording all measurements on a scale layout of the building containing the accelerator is advisable. The recorded measurements can be referred to during subsequent surveys to determine the cause of any changes that may have occurred in the levels.

Periodic surveys are useful not only for detecting abnormal radiation levels, but also to help familiarize personnel with the characteristics of the radiation levels normally present and the functioning of survey instruments.

Because most instruments are designed to measure steady sources of radiation, the fields produced by pulsed accelerators introduce a problem in the interpretation of the readings obtained. Electronic limitations of survey instruments (e.g., resolution, response time, etc.) may produce readings which indicate radiation levels considerably lower than the actual exposure. Before establishing a routine program of radiation surveys, it is therefore necessary to determine what levels exceed the capacity of the survey instruments. A method of calculating the effect of pulsed beams on the meter reading is explained in Appendix D.

### 4.7.3 Instrument Calibration

The radiation safety of any accelerator facility depends on the performance of the survey and monitoring instruments. While the calibration of these instruments is a specialized subject considered to be outside the scope of this Manual certain points and suggestions on the use of these instruments in accelerator facilities is included.

Instruments should be calibrated using secondary radiation standards at regular intervals. Each time an instrument is used, the user should be alert for possible malfunctioning, such as indicated by erratic reading, no reading, or rates of change in the readings that do not correspond to expected variations in radiation intensity. When such troubles occur, the operator must not necessarily assume that the meter is wrong, but instead should get another instrument or otherwise attempt to determine the true condition.

Fortunately, accuracies of 20 to 50 percent are usually adequate in practical measurements to determine if areas are safe to enter or work in. Such accuracies can usually be maintained by checking the meters with in-house radiation sources.

Reference sources are available from some laboratories which have the equipment necessary to calibrate the sources. Where possible, instruments should be calibrated by the use of a source whose size, energy, and intensity are similar to those to be measured.

Gamma and X-rays: Radiation survey instruments that measure gamma and X-rays can be calibrated by measurement of the radiation from radium, cesium and cobalt sources. The activity of such sources should be known, but in practice only the intensity of radiation at some specific distance (commonly expressed as roentgens per hour at one meter) is required.

The spectral sensitivity or energy dependence can be checked by using several radioactive sources of different energies. Available sources have energies ranging from 150 keV to several MeV. Some of these materials produce monoenergetic radiation; others have several discrete energies. Filtered X-ray beams are often used below 100 keV.

If thin-walled detectors are to be calibrated at distances of less than about one meter from a source, low-energy secondary electrons from the source container or the source itself may give false readings. A thin piece of lucite or other material equivalent to about a meter of air should be placed between the source and the detector to absorb the secondary electrons.

When instruments are to be calibrated at a different distance from a source than that at which the intensity is known, the inverse-square law is often used to find the intensity at the new distance. The calculated result and the energy spectrum can be different from the actual intensity and spectrum because of scattering from nearby objects (such as floors and walls) and absorption or other processes in the intervening air. It is possible to determine the variation in intensity with distance for a particular type of instrument, but the variation will be different with other types of instruments with different energy responses. Usually it is easier to arrange substantially scatter-free conditions by suspending the radioactive source so the distances from both source and detector to the closest scattering surface or object is larger than the separation between them. With such an arrangement, scattering will generally cause less than a ten percent error in the measurement (20).

If the detector is very close to the source, the radiation intensity may not be uniform throughout the volume of the detector. If the separation between source and detector is at least twice the largest dimension of either, this effect will cause less than a ten percent error.

Large sources may be directionally nonuniform because of self-absorption of the radiation in the source material. Directional properties of both the calibration source and the detectors should be determined, or fixed orientations used for repeated testing of instruments.

Neutrons: The accurate determination of neutron source strengths is difficult because there are many possible causes of error and the errors are difficult to evaluate. Radium-beryllium, polonium-beryllium, and other sources of known neutron output and energy spectrum are available. These sources can be used to standardize secondary sources, which in turn can be used for instrument calibration. A boron trifluoride counter can be used to compare the sources.

Routine calibration and checks of neutron detection instruments can be made by using a radium-beryllium or polonium-beryllium source of fast neutrons. The same source can be used with suitable moderators to produce low-energy and thermal neutrons. Typical sources yield about $10^7$ neutrons per second per curie of radium and $2 \times 10^6$ neutrons per second of polonium, both with a wide spectrum of energies. A Ra-Be source may affect the readings of some instruments which are sensitive to gamma rays, in which case a Po-Be source may be more desirable in spite of its shorter half-life and relative lower neutron yield (20).

When the inverse-square law is applied to calibrations using an unmoderated fast neutron source, the same considerations concerning scattering discussed under gamma and X-ray apply. Because there are wide differences in the low-energy response of instruments designed to measure fast neutrons, the effects of neutron scattering differ considerably. Scattering can be a cause of large errors and the effective neutron energy can change significantly when more than one surface is involved, such as the floor and walls of a room. The minimum source-to-detector distance is dictated, as it is for gamma ray sources, by the relative source and detector sizes.

A simple moderating arrangement for obtaining neutrons of low and thermal energies, consists of a Ra-Be source in the center of a water tank or paraffin block about 50 to 100 cm on a side. The thermal-neutron flux can be calculated as a function of the distance from the source. As an indication of the magnitudes involved, the approximate thermal neutron flux in water for distances $r$ greater than 12 cm from a Ra-Be source is given by $(0.7Q \exp -0.1r)/r^2$, where Q is the total number of neutrons emitted by the source per second, and r is in cm. (20).

The effects of the materials in the detector, especially the wall material, on the neutron energy distribution must be evaluated, as some fraction of the neutrons may be slowed to energies to which some types of detectors become insensitive.

### 4.7.4 Neutron Monitoring

Neutron radiation will be produced only when the accelerator beam is on. The flux of neutrons outside the shielding of a specific accelerator will depend on the use of the beam, the beam energy, the nuclear characteristics of the material being irradiated, and the nature of the shielding material. The purpose of a neutron radiation survey is to determine whether the flux outside the shielding is within safe limits.

Neutron radiation around particle accelerator installations will always be accompanied by relatively high levels of gamma radiation. Consequently, in order to measure the neutron flux adequately it is necessary to have an instrument insensitive to gamma radiation.

Because the neutron is not directly ionizing, the ionization measured by a survey instrument must be produced by reactions of the neutrons with material in the chamber wall or the gas in the chamber. The charged particles resulting from these reactions are what is detected in a neutron counter.

A "thin" detector is one which inserts very little matter in the path of radiation. Even a large gas-filled chamber is therefore "thin" compared, for example, to body tissue of the same dimensions. A thin detector, in which an interacting neutron will probably make only one collision, does not accurately indicate the amount of ionization which would be produced in body tissue where the neutron might collide several times. If a "thin" instrument is calibrated to measure the "first-collision" dose in rads (or the dose rate in rads per unit time), the ionization produced in the body by the same radiation will be higher. This is because more and more secondaries are produced as the primary beam penetrates the absorber. The ionization and absorbed dose produced in the body, will be the first-collision dose measured by the detector multiplied by a buildup factor. This buildup factor is a function of the depth in the absorber in which the ionization or dose is measured.

Because detection instruments are not all equally thin compared to the human body, the conversion of their response to dose in the body must be based on a buildup factor appropriate to the particular instrument and the energy spectrum of the radiation being measured. This factor may already have been applied if the meter is calibrated in dose units; otherwise, it will be necessary for the user to apply the factor to convert first-collision measurements to dose. The calibration procedure must be known before proper interpretation of the measurements can be made.

The radiation dose produced by neutrons is sometimes expressed in terms of the radiation dose produced by X-rays although, of course, neutrons cannot be standardized in terms of the ionization they produce in air. A radiation dose from neutrons in human body tissue is sometimes stated in terms of an equivalent dose caused by X-rays, and in this statement the unit of neutron dose is called "roentgen equivalent-man" and abbreviated rem.

Some instruments measure the neutron flux in terms of the number of neutrons incident on a unit surface per unit time, rather than measuring a quantity related to the radiation dose caused by the neutrons. If the energy of the neutrons can be estimated with reasonable accuracy, the approximate neutron flux equivalent to one 100 millirems per week may be found from Table 3 *(21)*.

Table 3. Neutron Flux Dose Equivalents *(21)*

| Neutron Energy (Mev) | Average flux to deliver 100 millirem in 40 hrs. (neutrons/cm$^2$ per sec.) |
|---|---|
| Thermal | 670 |
| 0.0001 | 500 |
| 0.005 | 570 |
| 0.02 | 280 |
| 0.1 | 80 |
| 0.5 | 30 |
| 1.0 | 18 |
| 2.5 | 20 |
| 5.0 | 18 |
| 7.5 | 17 |
| 10 | 17 |
| 10 to 30 | 10 |

In selecting neutron survey instruments for a specific accelerator facility, some general aspects of the detection instrument should be considered.

(1) The detection instrument may be calibrated either in first-collision neutron dose or in neutron flux. In either case, careful interpretation of the measurements must be made and the calibration procedure must be known.

(2) The gamma response or discrimination of the detector should be known in order that the gamma effects can be excluded from the neutron-field measurement.

(3) Like the response of any radiation detector, that of a neutron instrument is governed by statistical considerations. Since shielding evaluation may ordinarily encompass several orders of magnitude of intensity, the question of adequate sensitivity and linearity of performance over the whole range to be measured is fundamental.

(4) Although absolute dosimetry of neutron fields is an intricate problem that has not really been solved generally, relative measurements are frequently all that are required for shielding evaluation. Neutron flux measurements are more useful for shielding evaluation than are dose measurements. However, even flux measurements require a good reference standard to allow measurement of departures from calibration in the detector. The reference standard should have a spectral composition approximating the neutron field being measured.

Ionization instruments are usually not satisfactory for measuring neutron fluxes or neutron dose, since they are also sensitive to gamma radiation.

The boron trifluoride ($BF_3$) proportional counter provides a sensitive detector for a neutron survey instrument which can also be relatively insensitive to gamma radiation. The $BF_3$ counter makes use of the nuclear reaction $B^{10}$ $(n,\alpha)Li^7$. The instrument uses $BF_3$ gas enriched to more than 95 percent in the isotope $B^{10}$, and typically the detector has a 4-inch active length and 7-inch overall length. Counting efficiencies of $BF_3$ detectors are generally in the neighborhood of about 20 percent. A typical counter having a sensitive volume of 60 $cm^3$ and filled with $B^{10}$-enriched $BF_3$ to a pressure of 15 cm Hg would have a sensitivity of about 1.1 counts per neutron per $cm^2$.

The $BF_3$ counter is sensitive to thermal neutrons. To meet the requirements for a counter suitable for intermediate-energy and fast neutrons, the $BF_3$ counter can be enclosed by a polyethylene or paraffin moderator which moderates the neutrons before entering the $BF_3$ gas. By suitable selection of the moderator configuration, it is possible to achieve reaction rates which are substantially independent of neutron energy from 10 keV to nearly 10 MeV (22).

The development of good scintillation survey instruments to measure neutrons depends primarily on scintillating materials with the proper characteristics, since the circuits are essentially the same as those for measuring other kinds of radiation. Examples of scintillating materials used for neutron survey instruments are organic phosphors or proton radiating materials combined with scintillators for fast neutrons, and boron or lithium bearing phosphors for thermal neutrons. Materials sensitive to thermal neutrons can be combined with moderators to provide a detector which gives a rem response for thermal, intermediate, and fast neutrons.

### 4.7.5 Monitoring of Radiation Workers

Monitoring the exposure and dose to radiation workers can be accomplished by using pocket dosimeters, pocket ionization chambers, film badges and thermoluminescent dosimeters. Dosimeters and pocket chambers are usually limited to beta and gamma radiation. Film badges on the other hand can be made sensitive to gamma and X-rays, electrons, and neutrons. The use of filters makes possible the separation of different kinds of radiation and different energy ranges. Ionizing radiations produce blackening of the emulsion, which can be determined photometrically after development. Since it is possible to prevent the disappearance of the latent image by suitable choice and treatment of the emulsion, as well as by the air-tight enclosure of the film, an almost complete integration of the radiation dose for several weeks can be guaranteed. The continuous sensitivity and ease of handling of photographic film, as well as it being a permanent record of the radiation received, make film dosimeters particularly suitable for individual dosimetry and for periodic examination of the integrated exposure of persons constantly exposed to radiation.

If the operators of an accelerator installation do not want to become involved in the processing of film badges, they can subscribe to a film badge service. These commercial services supply, develop, and read the exposed film, and keep an exposure record for each individual.

### 4.7.6 Air Monitoring

A number of methods may be used to obtain air samples from target rooms, accelerator rooms and occupied areas. The most common air sampling device is filter paper through which air is drawn at a known rate. The method is suitable for all types of particulate material and even for certain mists and smokes. Sampling rates up to 50 cubic feet per minute can be used with some papers whose activity can be measured directly in a proportional or scintillation counter. Like all other instruments, air monitoring equipment must be calibrated to yield accurate results. Apart from the problems of calibrating counting equipment, there is the additional requirement for calibration of the air flow.

Additional monitoring devices should be available for hazardous gases in installations where they may occur. One such gas is tritium, which may be used as target material for the production of neutrons. Tritium is discussed in Section 4.4.3. Information about air concentrations can be obtained from the device known as the sniffer. This is an ionization chamber with a volume of 600 ml through which air is drawn at rates of about 10 $ft^3$/min. A modified survey meter amplifies the ionization current which is related to the concentration of radioactive gas in the air. If other sources of ions are present, such as radioactive materials, the ionization chamber may be preceded by an ion collector. In any case, the instrument should be calibrated against a known concentration of tritium gas under the actual conditions of operation *(20)*.

## 5. NONRADIATION HAZARDS AND SAFETY CONSIDERATIONS

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## 5.1 General

While this Manual emphasizes radiation hazards, the more conventional nonradiation hazards are no less important in the operation of accelerator facilities. In fact, the accidents experienced by the Atomic Energy Commission during the period of 1943-1964, incorporating the records of both the AEC and its predecessor the Manhattan Engineer District, were largely the result of physical factors and electrical and chemical phenomena, not the result of radiation.

During this period there were 251 fatalities from all causes in construction, plant and laboratory operations, and direct government activities *(23)*. Of this number 3 were due to radiation, 81 were due to falls or falling objects, 38 were due to electrocution, and 62 were due to motor vehicle and mobile equipment accidents. During the same period there were 15,790 lost-time injuries attributed to all accident causes. Of the lost-time injuries, 36 were caused by nuclear radiation. These figures do not reflect the accidents which did not result in cuts, bruises, tolerable radiation exposures, and exposures to toxic and potentially dangerous materials.

Persons responsible for safety at accelerator facilities should become familiar with the safety codes, standards, and federal, State and local regulations which apply to their particular facility.

## 5.2 Fire and Explosion Hazards

### 5.2.1 Accelerator Fire and Explosion Hazards

The principal fire hazard associated with particle accelerators is that of electrical fires. Fire prevention measures and fire protection equipment for electrical fires should be provided. Flammable oils, with their inherent hazard, are often used as heat-transfer media. Combustible liquids, solvents and gases are used in accelerator operation and maintenance. Accelerators themselves have an explosion hazard where explosive high pressure gas is used, for example, in a hydrogen target or where the accelerator is pressurized.

Accelerator fire prevention and protection measures commonly include location of hazardous equipment in detached noncombustible structures, automatic and/or remote electrical and fuel cut-offs, adequate drainage and ventilation, elimination of all combustible materials from the area, fire detection devices, and in some cases, specially designed fire extinguishing systems.

### 5.2.2 Fire and Explosion Hazards of Experimental Equipment

The fire hazard for experimental equipment is high when complex electrical apparatus is used in close proximity to flammable or explosive materials. Special fire prevention and protection measures are required and should be provided. Combustible liquids and gases are often used in accelerator experiments. A fire may damage containers, piping, or pressure vessels, as well as protective devices and fire-fighting equipment.

The hazards associated with experimental equipment often include the hazards of pressurized and liquified flammable gases. Common fluids and equipment encountered are:

| Flammable pressurized gases | Flammable liquified gases | Equipment involved |
|---|---|---|
| Propane | Hydrogen | Counters |
| Methane | Deuterium | Targets |
| Ethylene | | Auxiliary fluid handling and storage equipment |

Material subjected to bombardment by intense electron beams presents a fire hazard of unusual severity. This fire hazard may result from any one or a combination of three basic causes: (1) high rate of internal thermal input through energetic electrons stopping within the material; (2) radiation analysis of exothermic chemical reactions; (3) initiation of explosive reactions in volatile vapors through electrical breakdown and sparking. Because of their limited range, electrons are capable of delivering large quantities of energy within relatively limited volumes of irradiated material. Almost 100 percent of the energy of an absorbed electron will appear as local heating in the material. If the material is a poor conductor of heat, high internal temperatures may be produced. For this reason, processing of flammable products by a high intensity electron beam requires careful attention. An excess of beam on a flammable substance may ignite the product or trigger a reaction resulting in damage to nearby process equipment. When volatile compounds are irradiated, ventilation should be provided to prevent the accumulation of explosive concentrations of vapors, dusts, or gases.

Some recommended fire and explosion prevention measures for experimental areas include the following: (24)

(1) A periodic review of all current experiments should be made to evaluate the possible interaction of the hazards of each, with the equipment and materials of other experiments.

(2) Before approval is given for equipment and materials, as well as experimental procedures, consideration should be given to layout and design with regard to confining any potential incident to the smallest area practicable. Thus damage will more likely be absorbed within one area without propagating to others.

(3) The quantity of flammable materials in the experimental area should be minimized. Consideration should be given to isolating gas supplies and piping them to the experimental area.

(4) When large quantities of flammable gases are used, an emergency remote shut-off valve should be incorporated in each such piping system, if practical.

(5) Sources of ignition should be kept to an absolute minimum where flammable gases or liquids are used, or where flammable dust may be present. A review should be made of the potential ignition sources and the hazard that each presents. Where there is a likelihood of flammable gases, vapors or dusts entering the atmosphere of an experimental area, explosion-proof electrical equipment should be used in accordance with the degree of hazard. If such equipment is not available or its use not practical, continuous air or inert-gas purging should be considered. Arrangement of ventilation so as to establish regions of positive pressure should also be considered.

(6) All tubing and connections used in systems for flammable fluids should be examined periodically for ability to maintain integrity during extended periods under high temperature conditions such as might be encountered in a fire.

(7) Extreme caution should be used in the application of unique or exotic materials in experimental devices. Current literature relating to properties and experience with such materials should be reviewed. In-house testing programs should be undertaken, if necessary, to fill gaps in required safety information.

(8) The facility's electrical, ventilation, alarm, and other systems should be evaluated for each experiment, and particular attention be given to possible interaction of any of these systems in an emergency.

(9) Exhaust systems for flammable gases should lead directly to the exterior of the building without the possibility of discharging into the experimental area.

(10) Systems for the detection of flammable gases should be reexamined periodically to determine whether they can perform adequately. High and low spaces where gases can collect should be monitored continuously with permanently installed equipment or by portable devices on a schedule consistent with experimental conditions.

(11) All systems which may be put to use in an emergency should be subject to periodic testing. Alarm systems should be equipped with monitoring devices. Consideration should be given to the installation of a remote readout, with reset, for flammable gas and other alarm systems that would give information on the status of the experimental area after the building had been evacutated in an emergency.

(12) Wherever practical, the experimental area should be isolated from the accelerator by a fire and blast resistant wall to prevent or minimize damage to an accelerator resulting from accidents in the experimental area.

### 5.2.3 Equipment Operation in Hazardous Areas

It is essential to define a "hazardous area" for all equipment or components containing a flammable or explosive gas, and to establish special operating practices within this area. The definition depends on the size and nature of equipment and other potentially hazardous conditions located nearby. General guidelines for hazardous areas are listed below.

(1) Appropriate "flammable gas" warning signs should be posted inside hazardous areas and at entrances to the areas when equipment is filled with flammable gas. The signs should be removed when the hazard no longer exists.

(2) Sources of ignition should be eliminated in hazardous areas. If equipment of a type approved for use in the hazardous area is not available in the appropriate classification or its use not practical, the ignition sources in the equipment should either be removed from the hazardous area, continuously purged with air or an inert gas, or limited in ignition energy. All potentially hazardous equipment, including power supplies, motors, fill lines, and vent lines, should be electrically grounded.

(3) Ventilation of known direction and flow rate should be provided in hazardous areas to dissipate accidental releases of the flammable gases and to maintain concentrations below the explosive limits. Emergency forced ventilation should be used when hazardous areas are enclosed. Particular attention should be paid to the direction of flow of the ventilating air when the gases are heavier than air. The areas in which flammable gases may accumulate should be minimized and activities within the areas restricted. For heavier-than-air flammable gases, floor drains and trenches should be isolated from the hazardous equipment or be well ventilated.

(4) Potential fuel sources such as gas storage bottles should be located outside the experimental buildings. All necessary gas cylinders should be removed, gas cylinders should be secured, and the relief valves of cylinders of flammable gases that must be used indoors should vent into a closed system which discharges outside the building.

(5) Gas detectors and alarms should be provided for all systems containing flammable gases. Any space in which flammable gases can constitute a hazard should be ventilated or monitored with a gas detector.

(6) Properly functioning portable gas detectors should be available.

(7) At least two means of egress, independent of each other, should be available from hazardous areas, preferably located so that it is not necessary to travel more than 75 feet to reach the nearest building exit. Blind ended passages should not be permitted.

(8) Emergency lighting should be provided.

(9) Soft-solder joints, rubber hose, plastic piping or tubing, quick-disconnect fittings and glass components should not be used on systems containing flammable gases.

(10) Assembly, testing, and operating procedures should be promulgated.

(11) Equipment venting should include the following:

a. Every vessel containing a flammable gas should be connected to a building fixed-vent line.

b. Only one flammable-gas device or system should be connected to a vent line at a time.

c. Vent lines and associated equipment, including parts of experimental apparatus attached to the vent line, should be designed so that they do not fail when subjected to thermal changes.
d. All vessels and piping should have positive relief devices connected to the building fixed-vent system.
e. Consideration should be given to connecting mechanical vacuum pumps which can pump flammable gases to a separate metal exhaust line that vents to the outside of the building.

## 5.3 Mechanical Hazards

### 5.3.1 Falls

The incidence of falling accidents is higher than all other accidents in the AEC installations *(23)*. Unsafe conditions which cause falling hazards sometimes are tolerated in accelerator facilities because of the temporary nature of some experimental setups or shielding arrangements. Railings, ladders, catwalks, and platforms should be installed according to industrial safety standards wherever personnel are required to work, even in temporary setups.

Objects which are not bolted to the floor should be braced or arranged so that they can resist side forces of at least a fifth of their weight without overturning. Pipes, panels, or other components which could be stepped on under any circumstance should either be braced to withstand such loads, or be guarded against being stepped on. "No Step" signs are not sufficient.

### 5.3.2 Vacuum Systems and Related Components

Vacuum Pumps: Mechanical vacuum pumps used on accelerators are usually either oil-sealed vane pumps or Roots pumps. The area around an oil-sealed pump tends to become slippery as a result of condensed oil vapor and will present a fire hazard unless carefully maintained. Oil spills and leaks also contribute to the problem. Mounting pumps in metal trays can confine the oil to areas which are normally not walked upon.

Roots pumps use two meshing figure-eight-shaped rotors in a closely fitted assembly. Since these pumps will rotate by air pressure without being electrically driven, service personnel should make certain that these pumps are valved off from evacuated systems or other pumps before attempting to work on them.

Diffusion pumps are jet pumps using oil or mercury vapor. An electric heater vaporizes the working fluid, which flows from several annular nozzles in a central column and condenses on the cooled outer casing of the pump. Gas molecules entering the pump are struck by oil molecules from the jets causing the gas to move in the direction of the exhaust outlet near the bottom of the pump. Fluids used in these pumps must have a low vapor pressure. Personnel who handle or are exposed to such fluids should acquaint themselves with the degree of flammability or toxicity of the fluid being used. Particular care should be taken when mercury is handled.

Diffusion pumps with flammable oils should be protected against the possibility of exposure to air while the boiler is hot and should not be brought to atmospheric pressure until they have been cooled. The lower end of the diffusion pump contains the boiler. This portion of the pump becomes hot enough to cause burns. Thermal insulation should be applied to the parts which might be touched.

Ion pumps use high voltages to ionize and trap gas molecules. The electrical terminals to such pumps typically operate at several thousand volts and should be treated as a serious electrical hazard.

Glass or Ceramic Vacuum Components: The pressure difference between the atmosphere and a full vacuum at sea level is about one ton per square foot. Even a fraction of this difference can result in sonic flow velocity when air flows into the vacuum. For this reason, the accidental implosion of an evacuated brittle vessel may result in flying fragments with the velocities of bullets. Even though such fragments are initially propelled inward, they will glance and be propelled in unpredictable directions. Only those glass or pyrex vessels which are designed for such service should be evacuated. Protection against accidental damage to the vessel, and from fragments in event of an implosion, should be provided. A screen, box, or a heavy blanket around the vessel is usually sufficient. A sturdy transparent plastic panel can also be used as part of the enclosure if the vessel is to be observed. Evacuated flasks, jars, and dewars should be completely wrapped with adhesive tape.

Glass view ports also represent an implosion hazard. Glass is usually mounted against resilient supports to avoid stress concentrations. Care should be exercised in replacing a glass component to see that local stresses are not caused by improper arrangement of parts or over-tightened mountings.

Glasses and ceramics are structurally strong only in compression, but are vulnerable to rapid and catastrophic failure if they are overstressed in tension. Ceramic or glass insulators, rods, and sleeves should not be subjected to bending or tension loads for which they were not designed.

Ion gage tubes which project from vacuum equipment should be protected. A sturdy perforated metal cover will allow the gage tube to be inspected while providing protection against breakage and implosion.

Vacuum Vessels: Vacuum vessels should be designed to meet or exceed the requirements of the ASME code for unfired pressure vessels. Modifications to vacuum vessels should also be made in conformance with the ASME code. Structural hazards in vacuum vessels usually stem from instabilities or deflections due to external loading, rather than high stresses. Temporary setups for leak testing of vacuum vessels should recognize the structural contribution of any members for which substitutes have been used in the test setup. The substitute members, such as blank-off plates and braces, should be designed to maintain the structural integrity of the vessel. The danger of failure under vacuum is increased because of the impracticality of testing vessels at more than one atmosphere pressure difference.

Vessels should be shielded, or wrapped with a heavy blanket to protect personnel wherever such equipment is operated under conditions for which it was not designed. When positive-pressure leak tests are to be made on a vacuum vessel, the allowable pressure should be determined by a competent engineer. The reverse pressure can cause high forces which do not exist under vacuum conditions. A pumping or venting connection should be opened before applying heat to a vessel. A direct-reading bourdon vacuum gage connected directly to the vessel is desirable in any vacuum test setup. The gage reduces the chance of an accident occurring because of ignorance of the vacuum or pressure in the vessel.

Care should be taken in the use of clamps to hold temporary covers and joints. Evacuation of a vessel will often cause joints to close up tightly or gaskets to compress, and in so doing will remove the loading forces from clamps or bolts, allowing them to fall off. Returning the vessel to atmospheric pressure in such cases can allow cover plates to fall away, or joints to separate.

Valves: Valves which are pneumatically operated and large enough for a man to put a hand, arm, or leg through should be recognized as potential hazards. Since many valve control circuits are designed to cause the valve to close in the event of a power failure, electric circuits to the valve should be interrupted and air pressure vented before working near the valve. Securely placed braces or blocks capable of withstanding the full force of the operator should be used if there is any possibility of movement of the disc or gate.

Thin Windows: Thin windows are foil, plastic, or sheet metal diaphragms through which particle beams pass. They are usually highly stressed spherical or cylindrical segments which are held by a rigid gasketed frame. Stress concentrations can cause these windows to fail. Nicks, dents, fatigue, scratches, or overheating by the beam can initiate a failure. Periodic inspections should be made while the window is not under vacuum in order to avoid danger to the inspector. Windows should be shielded if work is to be performed near them. Windows should always be tested at considerably more than one atmosphere pressure difference by the use of test covers.

### 5.3.3 Magnets

Accelerator facilities usually include powerful magnets among their equipment. The largest components of the cyclotron and betatron are their magnets and particle beams are usually directed and focused by quadrupole and bending magnets.

The steel magnet yoke structure and magnet gap contains most of the magnetic flux. There is, however, leakage flux in the general vicinity of the magnet, increasing greatly in magnitude near the gap between the magnet's pole tips. Iron or steel objects brought near a large operating magnet, or left in a magnet which is turned off, can cause serious injuries. Since any movement of an object toward the magnet results in an increase in the attractive force, a paint can, wrench, or other common steel object becomes a potential projectile.

For the same reason the use of nonmagnetic structural or flooring components is advisable near magnets. Even though an initially assembled steel structure may be adequately strong to withstand magnetic forces, future maintenance, modifications, or repairs to the structure may leave some unrestrained part to the magnet's attractive forces.

Electrical conductors carrying high currents in the vicinity of a magnet are subject to electromagnetic forces. These forces are of most concern when the conductor carries direct currents.

Because of the forces noted above, all metal objects near electromagnets should be carefully secured. The possibility of overturning metal objects, or even the magnets themselves, should be considered where stand-mounted equipment is concerned. Rules should be established regarding the monitoring and use of metalic equipment and tools near magnets to minimize the possibility of accidents.

### 5.3.4 Liquid Pressure Systems

A fluid under pressure is a reservoir of potential energy which, if released in an uncontrolled manner, can cause serious injury to personnel.

Liquids, although often regarded as being incompressible, do, in fact, compress slightly. Containers with internal pressure expand elastically. Gases which are trapped or dissolved by surrounding pressurized liquid have potential energy. Because of such stored energy, the sudden failure of a vessel, closure, hose, or fitting, can release this energy and propel small parts, cause assemblies to fall or tip over, whip hoses, or spray fluids at high velocity.

Because of their compressibility, pressurized gases store much larger amounts of energy than do liquids. In addition to the danger of explosion, exposure of personnel to jets of gas, either by accident or during cleaning or processing operations, should be avoided. Eyes and ears are particularly vulnerable to jets of gas and high velocity particles, and should be protected from exposure to such hazards.

Exact procedures for the installation, operation and testing of pressure systems are usually specified by local, State, or laboratory codes, and should be followed. Pipes and vessels should not be heated, welded or soldered, unless they are vented, because of the pressure increase which may occur. Particular care should be exercised if a quantity of water or other volatile liquid could be in the system, since the pressure increase due to vapor generation may be many times that which would occur with only gas present. Similarly, repairs to a pressure system or its components should not be attempted until the pressure has been released, since the failure of a loosened component may be sudden and catastrophic. Pressure gages and pressure relief devices should be tested periodically and should not be relied upon as a guarantee of the existence of safe conditions unless their performance has been recently proved.

Hoses should be protected against damage due to kinking, twisting, abrasion, over-pressure, or mechanical loads. Hoses and the fittings used to couple them should be of types proven to be satisfactory for the system fluid, temperature, and pressure. Pipe nipples or pieces of tube should not be used as pressure hose barbs. The consequences of the failure of a hose or its fittings can be lessened by chaining the hose ends to the connecting system, or to substantial anchor points. Components which are vulnerable to mechanical damage, such as pressure gages, valves, and small tubing and piping, should be guarded against damage to protect personnel from the hazards which would result.

### 5.3.5 High Pressure (Cylinder) Gases

Gases which are supplied in cylinders deserve special attention and handling. The pressure in the cylinder is usually several thousand pounds per square inch and the gases may be toxic or flammable. Fittings for cylinders are designed to be compatible only with suitable connecting components, but no protection can be built in for careless use, or damaged or poorly-maintained equipment. No attempt should be made to continue to use equipment which leaks, malfunctions, or needs maintenance; such equipment should be clearly tagged and set aside for repair. The cylinder must restrain approximately a million foot-pounds of stored energy and thus must be carefully protected against any condition which could jeopardize its structural integrity.

The failure of a cylinder or its fittings may occur explosively, or may result in the cylinder becoming a high velocity projectile from the jet reaction of exhausting gas. Cylinders should be stored upright and secured against overturning. They should not be exposed to sources of heat and should never be dropped. Cradles should be used when lifting them with a crane, and dollys used to transport them. They should never be used as a roller or support. They should not be used where they may become exposed to flame, spilled cryogenic fluids, molten metal, or an arc welder.

Many serious accidents have occurred by accidentally mixing incompatible gases. Cylinders should be clearly marked, identifying the gas which they contain. Proper fittings should be used for the gases expected and adapter fittings should never be made. Pressure should be released using the regulator adjustment before slowly opening the cylinder valve. Stand clear of gauge faces when opening the valve. Never force a sticking valve, and keep the valve handle or key on the cylinder valve when it is in use. Never leave pressure in a hose that is not in use.

Some hazards are peculiar to the use of compressed oxygen. The combustibility of materials is greatly increased in an oxygen-rich environment. Fittings, lines, and regulators used with oxygen should be kept scrupulously free of grease and oil, since only minute quantities in an oxygen system can ignite explosively. Ordinary pipe thread compounds should not be used, but litharge and glycerine, or metal gaskets may be safely used. Oxygen cylinders should be stored separately from combustible gases to lessen fire and explosion hazards. Under no circumstances should oxygen be used to purge system lines, to operate pneumatic devices, or to dust off equipment or clothing.

Sulfur hexafluoride cylinders should be weighed to determine whether they are empty. If it is suspected that the liquid surface has frozen during a filling operation, rock the cylinder; DO NOT apply heat to the cylinder.

### 5.3.6 Lifting and Handling

Accelerator facilities usually include heavy equipment which requires great care in handling. The weight of items such as shielding blocks, magnets, and tanks should be marked with large painted numerals to reduce the possibility of attempts being made to lift or support them with equipment of inadequate capacity. Lift points should be selected to provide a stable condition for the lifted object even in the event that the object is bumped or tipped in the handling process. If possible, sufficient lift points should be used so that the failure of any one will not result in the dropping or an uncontrolled rotation of the object. The use of lifting fixtures with objects of odd or awkward configuration often saves time, in addition to making the handling job safer.

The capacity of equipment used for handling heavy objects should be clearly marked on the equipment. Maintenance and testing procedures should be established to insure that slings, shackles and fixtures are kept in safe condition. Handling procedures should be carefully supervised to avoid hazards associated with the improper arrangement and use of shackles, eyebolts, slings, and cribbing.

The operation of cranes in an accelerator facility requires even more care than in the usual industrial plant. The demands imposed by handling heavy or bulky objects in confined areas, and among delicate, expensive, and sometimes dangerous equipment, require that operating personnel be well trained and that signalmen and crane operators understand the meaning of all directive signals which are to be used. Cranes should not be operated unless the crane operator can see the areas to be entered or affected by the load, or can be directed by a signalman who can. Only one signalman should be used.

Lifts should not be made over personnel or equipment, when it can be avoided. Tag lines should be used to keep large objects under rotational control at all times. Loads should not be left suspended by an unattended crane. Hard hats should be worn in the vicinity of crane operations.

The crane should not be operated near an accelerator or experimental area without first determining from the area supervisor that it is safe and convenient to do so. Hazards such as those associated with the use of hydrogen, or other flammable or explosive gases, exposed electrical conductors, radiation sources, and fragile equipment should be identified and precautionary procedures determined by the supervisor. Magnetic objects should never be moved near operating magnets.

Heavy objects should not be placed on a truck or support structure without knowledge of its structural adequacy. When dollys are used to move objects, it is advisable that the center of gravity of the object be required to rise at least three inches before an unstable condition occurs. This provides protection against overturning in the event of a caster running against a stop. Swivel casters should be in their most unfavorable orientation when stability is checked.

### 5.3.7 Structural Hazards

New or relocated equipment should be installed only after confirming the adequacy of the supporting floor or structure. Before installing or modifying equipment, the effect on the environment or on other equipment should be evaluated. Water or combustible gas leaks near electrical equipment can be very hazardous. Newly installed equipment may deprive existing equipment of adequate water pressure or voltage, or its power dissipation may cause thermal hazards.

When modifications are to be made to existing equipment which could affect its structural strength, stability or electrical or operational safety, the modifications should be submitted for review by competent technical, safety, and operating supervisors.

## 5.4 Electrical Hazards

Accelerators require large amounts of electrical power and use this power in many diverse circuits. The circuits range from high voltage incoming supply lines rated at many kilowatts, to control circuits operating at small fractions of a watt but still using dangerous voltages. An accelerator, therefore, presents a broad range of electrical hazards.

The most serious danger is that of fatal electrical shock. However, nonfatal electric shocks can cause severe injury as a result of falls or impacts against nearby equipment. Electrical burns, caused by the passage of large current through the skin or through tissue, are often deep and painful, and heal slowly. Electrical accidents frequently cause serious damage to equipment, including damage by fire and smoke.

It is of great importance that personnel know what to do in the case of a serious shock. Speed in restarting the victim's breathing can mean the difference between life and death or irreparable brain damage. Because of the importance of speed in applying artificial respiration, persons exposed to electrical hazards should be required to practice the procedures and techniques recommended in electrical shock accidents so that they can apply them properly and rapidly.

In an experimental facility, it is impossible for designers to foresee all the hazardous situations which may later develop. In addition, the research personnel who use the equipment may be unfamiliar with the laboratory, personnel, organization and procedures. These circumstances require that everyone concerned must give special consideration to safety, both for himself and for others. Safe work habits are essential. Continuous emphasis should be given to the dangers that exist, so that familiarity does not lead to carelessness.

Persons doing electrical work on accelerators should bear in mind that several unusual factors exist which complicate their problems. The accelerator structures themselves, and any access ladders, platforms, or railings are usually a good ground. Work spaces are often confined and some distance above the floor so that the danger of falls and other mechanical injuries, as a result of reaction against even mild electrical shocks, is often considerable. Also, many insulating materials deteriorate after exposure to radiation, and though they appear intact, will crumble or flake off if touched. Ionizing radiation also can allow sparking to occur across normally adequate insulating materials, such as bakelite and micarta, leaving a carbonized path which may break down later. Short circuits may heat components to the point where high-power arcs occur.

No set of rules can be complete enough to insure safety and still allow reasonable efficiency in accelerator work. Every situation or event will require good judgment and intelligent application of the necessary safety measures to the particular problem of the moment. Each facility should develop its own safety procedures based on its own needs. These safety procedures should include the following:

(1) Never work alone on hazardous electrical equipment.

(2) Never take chances -- always assume circuits are energized until you have checked them.

(3) Avoid forming a circuit to ground through your body. Stand on insulating material and do not lean on metal cabinets or structures. Use one hand only.

(4) Follow approved tag-out and lock-out procedures. Remove fuses whenever possible to prevent accidental application of power.

(5) Make sure there is adequate light and free access to the equipment. Avoid working in confined or uncomfortable spaces.

(6) Provide and use grounding hooks on capacitor banks and high-voltage equipment.

(7) Follow good housekeeping practices.

### 5.4.1 Incoming Power Systems

Power is ordinarily brought to an accelerator facility in 3-phase, 3-wire high-voltage overhead lines, at 2400 volts or more, and converted to lower voltages in a transformer station. This station is often located outdoors, on a concrete pad separated by some distance from the buildings, and is surrounded by a substantial fence. Access to the transformer is by a gate which should normally be kept locked.

Maintenance, inspection and repairs in the transformer yard should be performed only by qualified electricians who are generally available from the plant maintenance staff, and therefore, laboratory personnel will seldom or never have occasion to deal with this equipment. Overhead lines are a serious hazard whenever large items of equipment are moved. AEC accident reports *(23)* list many fatalities caused by cranes striking overhead lines.

Recommended safe practices include: (1) being extremely careful when moving large equipment near power lines, (2) having all work on power lines and substations performed by qualified electricians, (3) staying a safe distance away from fallen power lines, and (4) posting warning signs of underground power lines and making available accurate maps.

### 5.4.2 Circuit Breakers and Distribution Circuits

Power from the main transformers is normally distributed to one or more circuit-breaker panels in 480V, 3-phase, 3-or 4-wire circuits, and reduced to 115V single-phase or 208V 3-phase for use in the accelerator. These circuits may be overhead, underground, in walls or floors, or in exposed conduit in accordance with applicable safety codes.

These circuits have high voltages and high current capabilities and their current-interrupting devices operate only at high current levels and afford little protection for personnel. Any repair or modification of these circuits should be done by qualified electricians.

Recommended safe practices include:

(1) The area around circuit-breaker panels should be kept clean, dry and well-lighted.

(2) Insulating material of rubber or wood should be provided in the area where persons stand to operate the circuit-breaker.

(3) Labels and signs identifying the circuit breakers and their circuits should be kept legible and up-to-date.

(4) Tag-out and lock-out procedures should be established and carefully followed before any work is done on these circuits.

(5) Any structural work near the circuit breaker panels or the circuits themselves should be conducted in a manner that prevents accidental contact with live wires. Drilling into walls containing concealed conduit or cableways should be done only when the location of the wires has been accurately determined.

(6) Exposed conduits and panels should be protected from mechanical damage by other equipment, such as heavy objects or fork-lifts. The area around conduit and panels should be kept clear of other equipment.

(7) All exposed metal surfaces (panels, conduits, etc.) should be securely grounded, by visible external grounds if possible.

(8) Meters without adequate capacity or insulation should not be used on tests on power circuits.

(9) Fuses larger than those specified may result in a hazardous condition and should never be used. When some of the fuses in a 3-phase system fail, power may still be applied to the fused circuit or equipment through the other lines. No repair or trouble-shooting should be attempted without recognition of this fact.

(10) Vacuum pumps and radiation monitoring equipment often have separate input power from other accelerator components, or have separate emergency power sources which supply power to these circuits even when the principal power source is turned off. Therefore, it should be remembered that dangerous voltages may be present at these points in the accelerator facility, even though the main circuit breakers have been opened.

### 5.4.3 Permanent Power to Accelerators

When an accelerator is installed in a building designed especially for it, the wiring can be installed in adequate conduit, cable trenches, etc. However, these circuits may be changed as a result of modifications to the accelerator, or the installation of additional equipment. Also, these systems are less conventional than those previously mentioned, and may have features which seem novel to maintenance electricians, or to accelerator and electronic technicians. Recommended safe practices include:

(1) Complete, accurate and up-to-date drawings should be kept, and should be carefully studied prior to any work on these circuits.

(2) The current-carrying capacity of this wiring should not be exceeded by the addition of new equipment.

(3) Great care should be taken when an accelerator is first installed or under construction, that power is not inadvertently turned on in circuits other than those being tested or used. It frequently happens that several components are being assembled and tested at the same time, and electricians, accelerator technicians, electronic technicians, as well as carpenters, plumbers, etc., are all working in the same building. Drawings may be incomplete or inaccurate, poor communication is likely to exist among groups of workers, and there may be a great deal of confusion and clutter in the building. If power is prematurely turned on, there may be an extreme hazard to personnel in the area, and to equipment that may be only partially installed.

### 5.4.4 Temporary Power for Experimental Set-Ups

Temporary power cables are often run to apparatus, such as large magnets, portable motor-generator sets, and electronic equipment in racks or on tables. Care should be taken to protect the cables and wherever possible they should be installed in cable trenches or metal cable trays. Equipment should never be rolled over the unprotected cables because of the danger of cutting the insulation which may cause an immediate or potential electrical shock hazard. If wires are suspended overhead, they should be securely supported, without kinks or excessive strains at the supports, and they should not be located in a position where overhead cranes, fork-lifts, or other mobile equipment could come in contact with them. Equipment should be properly grounded, and ground-return wires of adequate size should be provided. Loose cables should not be run on the floor where anyone could trip on them.

Temporary wiring should have adequate current-carrying capacity. It should be adequately secured, especially in the case of wires carrying direct current near magnets or wires which carry high-ampere pulse currents. The temporary wiring should have separate circuit breakers of proper rating, so power can be applied and removed without disturbance to other circuits. The circuit breakers should be clearly identified by suitable labels at the circuit breaker panel. Whenever possible, the temporary equipment should be clearly visible from the circuit breaker. When the equipment is disconnected or removed, the power cables should not be left connected to the circuit breaker.

### 5.4.5 High-Voltage Power Supplies and Capacitor Banks

Energy-storage systems are usually provided with bleeder resistors, dump switches, automatic grounding systems, or similar devices to remove the energy when power to the system is turned off.

Access doors to high-voltage equipment and in some cases to rooms containing this equipment should be interlocked to remove power and discharge capacitor banks if the doors are opened, and to discharge the capacitors when power is turned off by control circuits. These devices should provide clear visual indication of their safe or unsafe status.

However, these safety devices are never foolproof and may fail either electrically or mechanically. Also, many door interlocks can be manually reset to allow operation of the power supplies with access doors open. Grounding hooks (metal hooks connected to grounded portions of the structures by a long flexible cable, and having long insulating handles) should be available at each high-voltage power supply and capacitor bank. Recommended safe practices include:

(1) Inspect grounding hooks periodically to insure that all connections are firm and free of corrosion, and that the flexible cable is neither frayed nor broken.

(2) When connecting a grounding hook to a high-voltage terminal, do not touch the flexible cable, since high voltages may exist across the resistance of even a few feet of cable when contact is made to a high-voltage source.

(3) Remove grounding hooks before restoring power to the equipment.

(4) Capacitors should first be discharged through a resistor of sufficient resistance and wattage rating. The high-voltage terminal should then be securely connected to ground (or the terminals should be connected together if neither one is grounded), before any maintenance or repair work is begun on them. "Dielectric Relaxation" causes high voltages to develop across capacitors with the passage of time, even though they have been momentarily discharged and, for this reason, high-voltage capacitors in storage should have their terminals firmly wired together.

(5) The switches which control the power to high-voltage power supplies are often located in control rooms some distance away from the power supplies. Persons working on these supplies should insure that power cannot be turned on accidentally or inadvertently. This can sometimes be done by removing and retaining a master key from a switch in the control room, or by removing fuses from their holders.

(6) If high-voltage equipment is operated with its doors open, for example while trouble-shooting, personnel near the equipment should not look directly at the equipment if intensely bright sparks or arcs occur to avoid momentary blindness or permanent eye damage. Also, they should stay as far from the equipment as is practicable to avoid injury from flying objects. When a failure occurs in a high-voltage system and a large amount of energy is released in a small space, fragments of wire, metal, or glass are often dispersed with high velocity throughout the area. Capacitors may burst if one shorts internally and several others in parallel dump their energy through it. In such an event, the metal terminals of the capacitor are often propelled with considerable force.

(7) Most high-voltage equipment is enclosed either by solid metal or by wire mesh to prevent accidental contact by personnel. These shields should be firmly grounded at several points, by visible external grounds if practicable, and the ground leads should be protected from accidental damage.

(8) Low-voltage components associated with high-voltage circuits, for example, filament transformers for high-voltage rectifiers, should not be checked with hand-held voltmeters when the high voltage is on,

since the insulation may fail or arcs may occur as a result of the proximity of the measuring equipment.

(9) All vacuum tubes operating above 20 kV are X-ray sources and should be adequately shielded. In many, but not all cases, the tube envelope provides the shielding necessary.

(10) Mats of nonconducting rubber or other insulating material should be used on the floor in areas where access to exposed high-voltage equipment may be required.

### 5.4.6 Radio Frequency Systems

The equipment which furnishes RF power to an accelerator includes power supplies, modulators, pulse transformers, and large power tubes. Two general categories of hazard exist in this equipment; first, the electrical hazards associated with high voltage DC power supplies and capacitor banks (as discussed in the preceding section); and second, the hazard associated with radio-frequency power.

The power tubes used to generate RF power for linear accelerators and cyclotrons require pulsed voltages in the range of 20 kV to 200 kV or more, at high currents of over 100 amperes. In these accelerators, severe electrical hazards exist in the power supplies, modulators, and transformers which provide power to large tubes. When making klystron output power measurements, or when adjusting the tuning screws of tunable klystrons, a radiation hazard may exist. Appendix A discusses the production of X-rays by klystrons.

RF systems can produce intense local heating in nearby objects. Even though there is little RF power radiated from the RF system used with accelerators, the induction field near components such as tuning coils and dee transmission lines, may be intense enough to be a hazard. Metallic objects such as rings and watches may be heated to the point where burns result or tissue may be damaged even though metallic objects are not present. Damage to the eyes is especially serious because the lens tissue is not repaired by normal healing processes and permanent opacity may result from exposure to RF power *(25)*. Intense RF fields should be confined by metal or screen enclosures, both to protect personnel and to prevent radio interference as required by the Rules and Regulations of the Federal Communications Commission (FCC). If work must be done inside these enclosures, or with the enclosures removed, the power level should be kept low to minimize the hazard.

### 5.4.7 Instrumentation and Control Systems

The circuits of these systems usually operate at 125 volts or lower voltages. Occasionally DC voltages up to a few hundred volts are used in limited portions of the systems, and higher voltages exist in cathode ray-tube and closed-circuit TV systems.

Because personnel do not expect high voltages in control circuits, it is important to keep such voltages out of the control cabinets. Power circuits should also be kept out of control cabinets because the techniques and instruments used in control circuits and their testing can fail dangerously on power circuits. It is also important that all control power come from a common source and that interlock contacts operated by power contactors or breakers be supplied from the control power and not from the power circuit through the switchgear to which they are attached.

The operator's console and all other enclosures which can be contacted by personnel should be securely grounded to prevent electrical shock in the event of short-circuits or component failures inside the equipment. High-voltage and power cables should be run in separate wireways from control circuits.

Operating and maintenance personnel should always remember that console and meter indications present only indirect information about the condition of the circuits they monitor. There are often several intermediate components between the actual circuit element or voltage which is associated with the indication, and the indicator itself. These components may include resistors, capacitors, relays, etc., in addition to the panel light or meter itself. The fact that a meter indicates zero voltage, or that a light is out, does not present conclusive evidence. No circuit should be assumed to be de-energized, and therefore safe, merely because that condition is represented by the indicators.

The signal cables from ionization chambers, which are often used to measure beam intensity or radiation intensity, may conduct high voltages, especially if sparking occurs in the chamber. These cables should never be left without proper termination.

Interlock, control, and information circuits operate in a power-on condition or in a power-off condition. Personnel who are performing maintenance or trouble-shooting on these circuits should remember that negative information, for example, an unlighted pilot light on a display panel, may indicate only that a relay is in a certain position (open or closed), and that circuits normally open may be energized. Or it may indicate that there is no power to the display portion of the circuit.

Some power supplies are adjusted by motor-driven variable transformers. The control circuits to these motors are designed to drive the transformer to its zero-output position when the power supply control switch is turned off. Electronic control on regulation circuits also may have similar "automatic run-down" circuits. In the event of power failure or other trouble in the circuits, the automatic run-down may not operate. When power is restored, a high-voltage power supply may be fully turned on instantaneously, even though its control switch has been turned off in the interim. Any circuit or component known to have this kind of characteristic should have an appropriate sign or personnel safety interlock to prevent access in the unsafe condition.

### 5.4.8 Transformers, Inductors and Magnets

Any inductance, even one of moderate size, can store appreciable amounts of energy and will develop a very high voltage if current through it is interrupted. An automobile ignition coil operates on this principle by interrupting a current of a few amperes to develop more than 10 kilovolts. Great care should be taken when disconnecting the leads of any large inductance, to make sure that no currents, even very small ones, are flowing through it. It is a good practice to ground the terminals of an inductor before disconnecting the leads, if there is any possibility of such currents. Also, care should be taken when measuring the resistance or continuity of transformers, windings or magnet coils with a common ohm-meter, because severe shocks can be received if both hands are in contact with the coil at the instant that the meter probes are removed.

Current transformers can develop very high secondary voltages if the secondary circuits are left open. Such transformers should have their secondaries shorted if they are not in use. Transformers can also generate large amounts of heat and should be installed with adequate air circulation for cooling. Dust or moisture may collect on transformers inside enclosures, leading to possible arcing between the terminals, and hence these transformers should be inspected at appropriate intervals.

### 5.4.9 Interwiring (Wireways, Junction Boxes, Terminal Boards and Patch Panels)

Wireways are used to protect wires and cables from physical damage. Although the size, type and location of wireways are determined before an accelerator is installed and the wireways are constructed at the time of the installation, changes in interwiring are made from time to time. Wireways tend to become excessively crowded, wires become tangled, unconnected wires are left in place, and labels and cable tags become detached. All these changes can lead to hazards. Insulation may fail because of overheating, the pressure of taut cables on others, or kinks. Grounding wires may become loose or wires may be incorrectly identified. For these reasons, wireways should be kept clean and in order. When new wires are installed, care should be taken to avoid damage or excessive strain to existing wires. Unused wires should be clearly labeled as spares, or removed. Water, dust, and metallic objects, such as chips, nuts and bolts, etc., should not be allowed to accumulate in wireways. Heavy or sharp-edged objects should not be allowed to rest on wiring.

These same considerations apply to terminal boards and junction boxes. The exposed terminals in these components present additional problems. High-voltage and high-power circuits and terminals should be kept physically separate from low-voltage control and instrumentation circuits. Terminals which present severe hazards, such as 480 V 3-phase terminals, or those in high-voltage circuits, should be identified by conspicuous labels or colors, and protected by insulation covers (such as lucite or micarta panels on standoffs) to prevent tools or other objects from being dropped onto them.

Unconnected cables and connectors at junction boxes and patch panels may be a potential hazard. If the circuits can be energized, the cables should be either connected or secured in a manner that prevents accidental contact by personnel or conducting objects. Caps should be installed on exposed connectors.

Insulation which is exposed to high radiation levels may deteriorate, and generally become brittle or flaky. The insulation on wiring in the target area of an accelerator should be inspected occasionally, as well as when there is evidence of deterioration, or whenever work is to be performed in the near vicinity of the circuits. The rate of deterioration will depend on many factors such as the type of insulation used, the kind and intensity of radiation, and its duration.

### 5.4.10 Miscellaneous High-Voltage Components

Several of the smaller components of an accelerator, located at various scattered points throughout the facility, use voltages high enough to present serious hazards.

Ion chambers are often used to measure radiation levels at the output of an accelerator, or to measure beam intensity or beam position near the target. These chambers may use DC voltages of about 1000 volts, and may have exposed terminals or connections in the wiring to their power supplies. The ion chambers are seldom used except when the accelerator is on and personnel are not near the target area. Consequently, the insulation and protective enclosures for these devices are less complex than for other devices where personnel are in frequent proximity. Also, they are exposed to high radiation fields, where ordinary insulation deteriorates rapidly. These ion chambers often have separate power supplies which can be turned on independently of the other accelerator components. Personnel working on such devices, or near them, should be aware of the possible hazard.

Ion vacuum pumps are often used to maintain high vacuum in accelerators. These pumps are powered by supplies which can deliver substantial current at voltages up to about 5 kV. To maintain the vacuum these pumps are usually energized even when all the other accelerator components are turned off. Personnel working near these pumps and power supplies should be aware of the hazard and should avoid careless handling of the cables and connectors.

Cathode-ray tubes, closed-circuit TV systems, and other electronic devices use very high voltages and appropriate care should always be taken when such devices are used with their protective covers removed. Commercially-manufactured instruments are usually well-designed and the hazards are clearly indicated by signs which are visible when the covers are removed. "Home-made" or modified devices should incorporate appropriate enclosures, interlocks, and signs.

A special category of devices which present extreme hazards is that of injectors, electron guns, and ion sources. Some of these devices use high DC voltages to focus, accelerate or control an ion beam and introduce it to the main accelerating structure. Typical linac injectors may use small Cockroft-Walton generators providing up to 200 kV while others may use pulse-transformers providing pulses up to this voltage. These voltages are high enough to create ionization of the surrounding air, and can therefore cause sparks in air over very long paths. Personnel should be kept a safe distance away from terminals and conductors which operate at these voltages.

Storage capacitors, such as those used in Cockcroft-Walton generators, can present lethal hazards if their bleeder resistors are damaged during operation and the bleeder circuit is open. Each storage capacitor should be separately discharged before any work is begun on the injector circuits.

## 5.5 Toxic Material Hazards

A toxic material is any substance which has the capacity to produce personal injury or illness through ingestion, inhalation or absorption through any body surface (26). All chemicals should be regarded with suspicion until proven to be nontoxic. Many chemicals, solvents, and metals used in accelerator installations have known toxic properties and standard handbooks on toxic materials should be available for easy reference. Accidents involving toxic materials are often of the kind that can leave the victim blinded or disfigured for life.

General suggestions for the use and handling of toxic materials are as follows:

(1) Toxic gases and vapors should be neutralized or chemically combined in preference to venting them to the outside air. When venting is necessary, vent lines should discharge well above the roof of the building.

(2) Operations involving toxic chemicals should be carried out in a fume hood if the chemicals used are gases, volatile liquids, or finely divided solids which might float into building working areas.

(3) Containers of especially toxic materials should be kept in a fume hood during use and storage. This should be done with such materials as small cylinders of hydrogen cyanide, carbon monoxide and boron trifluoride.

(4) Gas masks equipped with the proper canister should be easily available while toxic chemicals are being used.

(5) Smelling or breathing unknown or possibly toxic samples should be avoided.

(6) Toxic or hazardous chemicals should never be transferred from their original containers without labeling the new container.

(7) The contents of any chemical container whose label is illegible should not be used. The chemical should be disposed of by a person trained in chemical disposal techniques.

(8) Special caution should be used when working with especially poisonous materials, such as hydrogen cyanide. The work should be performed in a fume hood or out of doors. Be sure that at least two persons are in the area.

(9) Food and drink should never be stored in cold boxes, refrigerators or $CO_2$ chests used for sample storage.

(10) Hands and face should be washed thoroughly before eating and always immediately after use of any dangerous or toxic chemical.

(11) All chemicals and solvents should be stored and retained only in approved containers for the particular substance.

(12) Safety showers and eye wash fountains should be located near areas where toxic chemicals are used and stored.

### 5.5.1 Ozone Production

Accelerators which produce high intensity electron beams for industrial processing, not only may produce significant levels of radioactivity in the target room air but may also produce toxic quantities of ozone. In addition, ozone may be produced by corona discharge around high-voltage terminals.

Ozone is a strongly oxidizing gas which attacks metal and rubber rapidly. The effects of ozone are mainly on the respiratory system. Air concentrations of ozone in excess of a few tenths of a part per million cause discomfort to exposed individuals in the form of headache, dryness of throat and mucus membranes of nose and eyes following exposure of short duration *(27)*. Ventilation should be provided in irradiation and vault areas to reduce the hazard. Sufficient time should be allowed after the accelerator has been shut off and prior to entering the irradiation room or vaults, to permit the ventilation system to lower the ozone concentration to a permissible level. Concentrations should be checked by using a suitable instrument. The concentration of ozone produced by an electron beam passing through air, and the time which should elapse before personnel may enter the target cell after the beam has been turned off, may be determined by the methods described in Appendix C.

"G" values (the number of molecules reacting per 100 eV of energy absorbed) as high as 15 have been reported for the production of ozone in air *(28)*. Actually much higher values have been calculated and reported but do not appear to be experimentally reproducible. Frequently reported G values are between 3 and 9. A value of 6 can be used for rough calculations *(29)*.

In addition to ozone, many oxides of nitrogen are formed in the irradiation of air. Ozone, however, may be considered the most toxic compound formed *(30)*.

### 5.5.2 Gases

Nontoxic, but suffocating gases, are extensively used in accelerator laboratories. Such gases may accumulate or be confined in an area, and those that are heavier than air will accumulate near the floor and in gutters, pits, and other depressions. Gas accumulating in these low places could be fatal to maintenance personnel working on cable assemblies and other equipment located in them. Gases lighter than air will collect under the roof and in the case of hydrogen will create a significant explosion hazard. Areas where gases accumulate should be recognized as hazardous and the proper ventilation provided.

Care should also be exercised when performing operations, such as welding, which produce inert or toxic gases in confined areas. Adequate ventilation should be provided.

### 5.5.3 Metals with Toxic Properties

Many metals are toxic, as are many compounds formed by metals when exposed to laboratory chemicals. A few of the most serious hazards due to metals often used in accelerator facilities are described below. This listing is intended to indicate the nature and severity of hazards easily overlooked. Safety supervisors should be aware of the toxic properties of the metals commonly used in the facility and should study the toxic properties of unusual metals before their use is approved.

Beryllium: Beryllium metal and its oxides are widely used in the field of nuclear energy. The health hazards of beryllium are as follows:

(1) Metallic beryllium, its alloys, beryllium oxide hydroxide, or beryllium salts, when inhaled as mists, dusts, or fumes, may cause acute or chronic disease. Inhalation of beryllium compounds is known to have produced serious lung disease. Deaths have occurred as a result of acute and chronic exposure.

(2) Introduction of metallic beryllium, beryllium oxide, or beryllium salts into open wounds may result in abnormal tissue growth.

(3) Skin irritation may result from direct contact with beryllium fumes or compounds. This irritation is not experienced when handling solid beryllium or beryllium oxide.

(4) Pulmonary cancers in animals have been produced experimentally by inhalation of pure beryllium sulfate mist.

(5) A hazardous concentration of beryllium fume may occur when the metal is heated above 1400°F (760°C).

(6) A hazardous concentration of beryllium oxide fume may occur when the oxide is heated above 1300°F (704°C).

At present there are no detection devices which can warn people that dangerous concentrations of beryllium exist in the working atmosphere. For this reason operations involving the generation of beryllium fumes, mist, dust, or vapor should be done under controlled conditions. Beryllium and its compounds in powder form should be confined to ventilated hood or drybox operations. The working area should have a negative air pressure with respect to adjacent areas, since the negative pressure will help limit the spread of air-borne contamination.

Any operation which produces a dust, vapor, mist or fume, such as machining, grinding, welding, cutting, drilling, sawing, and milling, should be enclosed and exhaust-ventilated through high-efficiency filters. For dry operations, the volume of air required is 300 cubic feet per minute per square foot of open door area. The minimum face velocity required at any point in the opening is 240 feet per minute. In wet operations the volume of air required is 150 cfm/sq. ft. of open door area and the minimum velocity at any point is 120 fpm.

High-efficiency filters or other suitable air cleaning systems may be required if the exhaust creates a potential air polution problem.

Cadmium: Cadmium is used as a protective plating on iron and steel articles. Many bolts, fasteners and other mechanical and electrical components are cadmium plated. Cadmium is also an ingredient in many solders. Compounds of cadmium are frequently used as pigments in yellow, orange and red paints.

Deadly fumes may be given off from cadmium and its compounds above its melting point of 610°F. Death or serious illness can result from a single short-time exposure to cadmium fumes. Cadmium-plated articles are frequently mistaken for zinc coated items which are not seriously toxic. Poisoning can result from foods or drinks prepared or stored in cadmium-plated containers.

Welding, soldering or any high temperature heating of cadmium, cadmium-plated parts, machinery or equipment coated with cadmium, or cadmium-pigment paints should be done in a ventilated hood. If a hood is not available, personnel should be supplied with airline respirator equipment when work is to be done within a building or a confined space. When the work is to be done in the open and out of doors, personnel should be equipped with a respirator containing a metal fume cartridge.

Mercury: Mercury is used in manometers, thermometers and other laboratory instruments, relays, switches, batteries, transistor power supplies, some electronic tubes, and diffusion pumps. Mercury, although a metal, vaporizes slowly at room temperature and thus contaminates the air whenever it is exposed. This condition may result from open containers, spills, instrument breakage, and manometer blowouts. The health hazards of mercury are as follows:

(1) Repeated inhalation of the mercury vapors may result in severe cumulative poisoning *(27)*. At elevated temperatures short exposures may be fatal.

(2) Liquid mercury can be absorbed through the skin to produce the same effects as from inhalation. Skin contact should be avoided whenever possible and protective clothing should be worn.

Precautions which should be used with mercury are:

(1) Following a spill, personal clothing should be checked for the presence of mercury. Spilled mercury can be accidentally deposited in trouser cuffs, pockets and crevices in clothing.

(2) Skin contact with mercury should be avoided and protective clothing should be worn.

(3) Smoking or eating should be prohibited in areas where mercury or mercury compounds are used.

(4) Hands should be washed frequently. General cleanliness is important in reducing the possibility of absorption through the skin.

(5) Areas in which mercury has been spilled should be monitored and decontaminated as quickly as possible. Until the area is decontaminated, personnel access should be prohibited.

(6) Good ventilation should always be provided. Local exhaust ventilation may be required depending on conditions.

(7) Mercury traps and check valves should be used on equipment and instruments to avoid blowout.

(8) Plastic or metal containers should be used to contain mercury and plastic funnels should be used during transfers. Transfers should be made over catch pans.

(9) Mercury containers should be kept closed when not in use.

(10) Mercury should not be used in or around systems containing ammonia.

(11) Mercury spillage should not be disposed of in sewer drains.

Mercury batteries also present considerable hazard. They may explode when exposed to excessive heat or when shortcircuited. The resultant shrapnel and mercury contamination may be dangerous. The following precautions should be used.

(1) Store mercury batteries in their original container or enclosed in a nonconducting material.

(2) During storage, all uninsulated wire ends should be taped.

(3) When soldering leads, a heat sink should be used to absorb excess heat.

(4) During installation, precautions should be taken to prevent the development of a chort circuit.

(5) Used batteries should be discarded with all exposed surfaces and wires taped.

Lead: Lead is commonly used in accelerator installations for radiation shielding. Handling of the metal is unlikely to lead to absorption and lead poisoning. The most usual manner in which lead absorption occurs is by inhalation of the fume of molten lead or by inhalation of fine particles of metallic lead or its salts. The dust of lead oxide which arises from the bulk handling of old lead could, however, be dangerous, especially from inhalation. If buffing operations are done on a lead surface, enough fine dust in the 5-micron range may be thrown off to cause rapid lead poisoning by absorption through the lungs. Preventive measures used when working with molten lead should include adequate ventilation. A respirator should be worn when working with old lead because lead oxide may be present in significant quantities.

Uranium: Uranium may be used for gamma shielding in some accelerator installations. If the material is used it should be clad or precautions taken to control oxidation and subsequent spread of radioactive and toxic particles. Some beta and low-energy gamma radiation from the material may also be present. However, the radiation is significant only if the uranium surface to which personnel are exposed is large, or dust is inhaled or ingested. Any fabrication or machining of uranium should be done under controlled conditions and preferably within enclosures. Uranium dust will explode if exposed to a flame, and solid uranium will burn when exposed to heat or flame.

### 5.5.4 Other Hazardous Materials

Only a few of the more common hazardous materials which may exist in accelerator installations have been discussed. If new materials are brought into the accelerator facility they should be thoroughly investigated before permission is given for their use. All materials in general use should be investigated for the toxicity, fire, and explosion hazards which they may create. Additional consideration may be necessary when materials are used in a variety of situations with variations of temperature, pressure, and radiation. Most of the information required on handling of common toxic materials is readily available in handbooks of properties of industrial materials.

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# 6. RESPONSIBILITIES FOR ACCELERATOR SAFETY

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## 6.1 The Accelerator Safety Program

No accelerator facility should operate without an adequate safety program. However, one plan for safety organization will not fit all types of accelerator facilities. The program can be effective only through the actions of a safety organization which meets the needs of the facility.

The safety program should be designed to protect personnel from injury and equipment from damage. It should: (1) maintain safe working conditions; (2) enable the facility to meet its statutory and legal obligations, such as Federal, State and local requirements, regarding safe conditions, workmen's compensation matters, and liabilities related to injuries; (3) establish procedures and organizations to deal with emergencies, such as fires, explosions and radiation accidents; (4) conduct necessary inspections; and (5) instruct personnel in safe attitudes and practices.

Accelerators are complex, and personnel require long periods of experience and training before they become aware of all the hazards which exist or may develop, and before they become familiar with the appropriate safe practices. This is especially true of radiation hazards. It is also true of the many conventional hazards which may exist in novel equipment and surroundings.

The establishment and support of an effective safety program is, ultimately, the responsibility of the director of the accelerator facility. He should clearly establish the areas and levels of authority for the actual conduct of the program, because everyone in the facility must contribute to it if it is to be completely successful. Furthermore, the staff looks to the director for their definition of the status of safety, compared to the more interesting objectives of research results and publication.

Supervisors at all levels should be responsible for the safety of their groups, and should aggressively promote the safety program. All personnel should be informed through appropriate safety training of the hazards and recommended safe practices related to their work. Every individual should take the initiative in recognizing the hazards which he encounters, and in taking the proper precautions in his work. However, depending on individuals to take appropriate action in all situations will not obtain the desired results. Preventive measures by the safety organization, throughout the installation, are a necessity if individuals are to be fully protected.

Any safety program has to strike a balance between minimizing risks and maximizing the use of the facility. At the same time a proper safety program should cause negligible interference with the work of the facility. When this small interference and expense is compared with the cost of possible accidents, no one should object to a properly planned and administered safety program. The establishment and rigorous support of operating and radiation safety procedures in accelerator operation and maintenance is of utmost importance. The accelerator safety program should assure:

(1) That an adequate organization is established to formulate, advise on and implement safety policy, beginning at the time the facility is first proposed.

(2) That buildings and facilities provide an environment for safe conduct of experiments or production, and limit the extent of damage caused by any equipment malfunction.

(3) That safety is integrated in a project from its beginning and that the project is periodically reviewed by responsible persons to insure that continuing consideration is being given to problems of safety.

(4) That there is an identification and evaluation of hazards at all stages of an experiment or irradiation process-from conception through operation and deactivation.

(5) That there exist multiple and, where possible, sequential safeguards to provide defense in depth in the event of equipment failure and/or human error.

## 6.2 Organization for Safety

Organization for safety in an accelerator installation should provide for radiation safety, accelerator safety, and general safety. It may be necessary to form a general safety committee whose members, in a large facility, would represent management, health physics, engineering operations, research and the user groups. The safety committee should review proposed experiments, facility changes or deviations from standard operating procedures. The safety committee should also compile and publish rules and procedures for safe practices in their facility. The functions of the safety committee should include the following:

(1) Formulate safety policy.
(2) Establish review procedures and standards.
(3) Coordinate and review safety activities.
(4) Examine requests for variances.
(5) Advise the director, staff and user groups on safety matters.

### 6.2.1 Radiation Safety

Responsibilities for radiation safety should include:

(1) Inventory and control of radioactive sources, targets and other activated materials.

(2) Observation and control of radiation hazards.

(3) Radiation waste storage and disposal.

(4) General radiation monitoring procedures.

(5) Instruction of personnel in observation of rules and monitoring procedures.

(6) Maintenance of records related to exposures and accumulated doses received by the personnel.

(7) Periodic routine survey of the accelerator installation.

(8) Surveys of new experimental setups.

(9) Survey of unusual conditions including conditions during maintenance operations.

### 6.2.2 Accelerator Safety

The person in charge of accelerator safety should have an adequate background of experience related to the accelerator. He should be responsible for the mechanical and electrical safety related to:

(1) Target systems.

(2) Beam transport systems.

(3) Auxiliary mechanical equipment.

(4) Special fire protection.

(5) Control systems.

In addition, he should be responsible for instruction of accelerator operators and technicicans, should keep the operator adequately informed of the radiation fields, and should disseminate information about safety procedures and special hazards.

### 6.2.3 General Safety

Responsibilities for general safety procedures should include:

(1) Storage and safe use of chemicals.

(2) Storage and safe use of gases.

(3) Safety supplies.

(4) Machine shop conditions.

(5) Elimination of fire and mechanical hazards.

(6) Emergency lighting and power.

(7) Maintenance and use of special safety equipment, such as ventilation systems, respirators, safety glasses, self-contained breathing apparatus and air sampling equipment.

(8) Review of handling procedures involving toxic materials.

### 6.3 Standards and Recommendations

The safety standards which are adopted in each facility depend somewhat on the local State and Federal regulations in effect. Standards which may be used as guidelines are included in the Reference and Bibliography section.

NCRH recommendations for the safe operation of particle accelerators are included in Appendix E.

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## Appendix A

## PRODUCTION OF X-RAYS BY KLYSTRONS

The combination of high voltage and high power in klystron tubes produces conditions for the generation and release of considerable amounts of X-radiation. The importance of this hazard has been shown by one incident in which four persons received exposures of several hundred rem from klystron X-radiation (31).

The following approximate calculation of the dose rate from a klystron follows the method of Wong (32). The dose rate in roentgens per hour is given by:

$$I = \frac{24 \times 10^{-7}\ VP}{r^2}$$

where

$V$ = klystron tube voltage, in volts
$P$ = klystron average power, in watts
$r$ = distance between the klystron collector and point at which the dose rate is observed, in meters

The results are said to be accurate to within plus or minus 25% for tube voltages between 60 kV to 600 kV. The radiation should be considered isotropic.

In determining the shielding required, the tube potential should be multiplied by 2 to assure adequate shielding of the klystron, even under abnormal tube behavior. This correction of the tube potential is believed to be conservative by an order of magnitude for the normally operating tune at about 200 kV.

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## Appendix B

## ACTIVATION OF AIR BY ELECTRON BEAMS *(29)*

Above the threshold energies for the $^{14}N(\gamma,n)\ ^{13}N$ and $^{16}O(\gamma,n)\ ^{15}O$ reactions (i.e., 10.6 MeV and 14.7 MeV, respectively), if one considers only $^{13}N$, which has a half-life of 9.96 minutes and is the most abundant, the calculation is somewhat simplified. It is possible to predict the amount of $^{13}N$ produced by an electron beam in air from the following equation:

$$M_o = \frac{100\ E_o^{1.5}\ D(E_o-E_t)^3}{1000 + (E_o-E_t)^3}$$

where

$M_o$ = Saturation level of $^{13}N$ in microcuries/milliampere
$E_o$ = Electron energy in MeV
$E_t$ = Threshold energy for $^{14}N(\gamma,n)\ ^{13}N$ = 10.6 MeV
$D$ = Path length of electron beam in air, in cm

Figure 12 derived from the above equation, shows the saturation levels for $^{13}N$ per milliampere of electron beam current for energies of 10 to 40 MeV.

The rate at which the $^{13}N$ decreases in the cell is a function of the cell exhaust rate and the physical half-life of the $^{13}N$. This rate of decrease may be determined by the following equation:

$$m_1 = m_o \exp - \left(\frac{v}{V} + u\right)\ t$$

where

$m_1$ = Microcuries of $^{13}N$ in cell after time t
$m_o$ = Saturation quantity of $^{13}N$ in cell in microcuries
$v$ = Cell exhaust rate in $cm^3$/min.
$V$ = Cell volume in $cm^3$
$u$ = Reciprocal lifetime of $^{13}N$ = 0.0606 $min^{-1}$
$t$ = Time after shutdown in minutes

(note that $\frac{v}{V}$ is the number of air changes per minute)

Figure 13, derived from the above equation shows the time required after shut-down of a 24 MeV, 750 microampere electron beam having a one meter path length for the $^{13}N$ level to decrease to $2 \times 10^{-6}$ microcuries/$cm^3$, the maximum permissible concentration for occupationally exposed personnel recommended by the International Commission on Radiological Protection *(33)*.

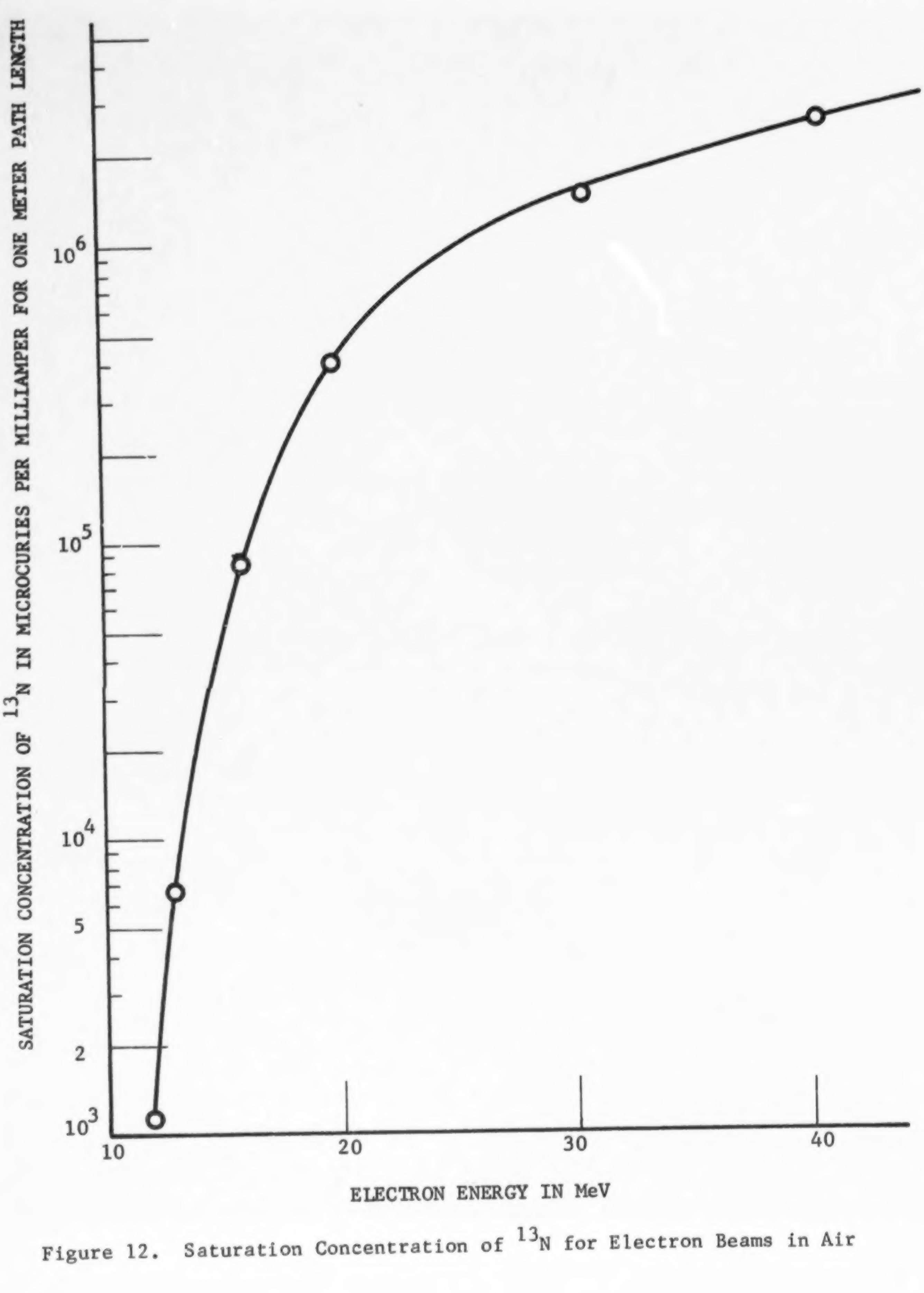

Figure 12. Saturation Concentration of $^{13}N$ for Electron Beams in Air

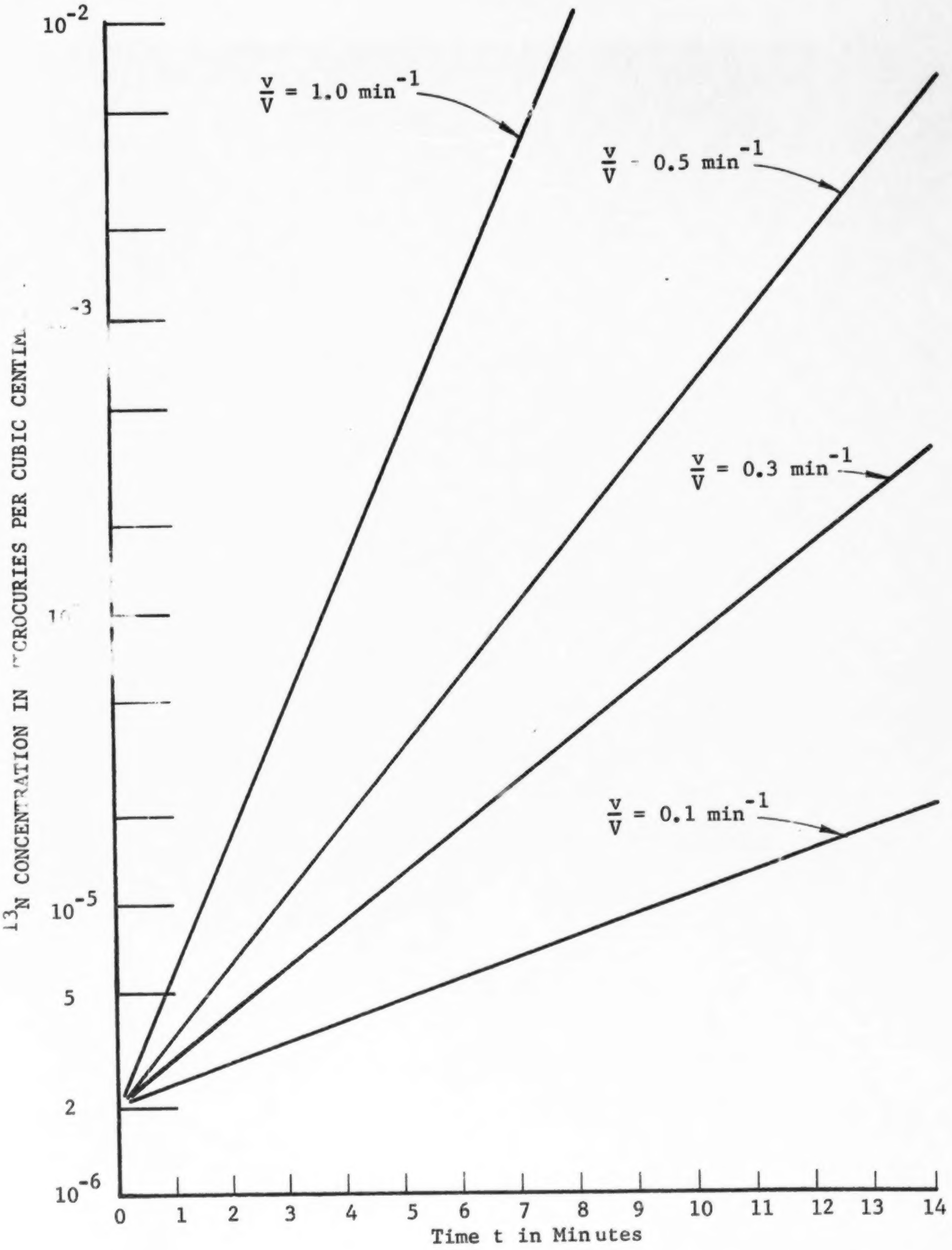

Figure 13. Time Required for the $^{13}$N Level to Decrease to Two Picocuries per cm$^3$

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## Appendix C

## PRODUCTION OF OZONE BY ELECTRON BEAMS (29)

The production of $O_3$ is governed by the following equation:

$$M_o = 360 \frac{GiD}{v} (1 - \exp \frac{-v}{V} t)$$

where

$M_o$ = concentration of ozone in the target cell.

$C$ = molecules of ozone formed per 100 eV = 6
$i$ = beam current in amperes
$D$ = beam path length in air in cm
$v$ = exhaust rate in $cm^3/min$
$V$ = cell volume in $cm^3$
$t$ = time in minutes from start of irradiation.

After machine shutoff the rate at which the ozone is removed from the target area, assuming recombination is negligible, is a function of the volume of the target cell and the rate of exhaust. The concentration of ozone in the cell at any time, assuming uniform distribution is given by

$$M_1 = M_o \exp \frac{-v}{V} t_1$$

where

$M_1$ = the concentration of ozone in the cell at time $t_1$

and

$t_1$ = the time in minutes after shutoff

Figure 14 shows the time which must elapse to allow the concentration of ozone to decrease to 0.1 ppm. In the figure $\frac{V}{iD}$ is plotted against t for several v/V ratios. It should be noted that for facilities operating well above the energy threshold for $^{13}N$ and $^{15}O$ production, the time before entering is governed by the concentrations of these radionuclides, and not the ozone.

The above equations make it evident that the experiments should be designed such that the path of the electron beam in air is short. The exhaust should preferably be close to the beam output. In this case the equations which are based on uniform distribution of $O_3$, are a conservative estimate.

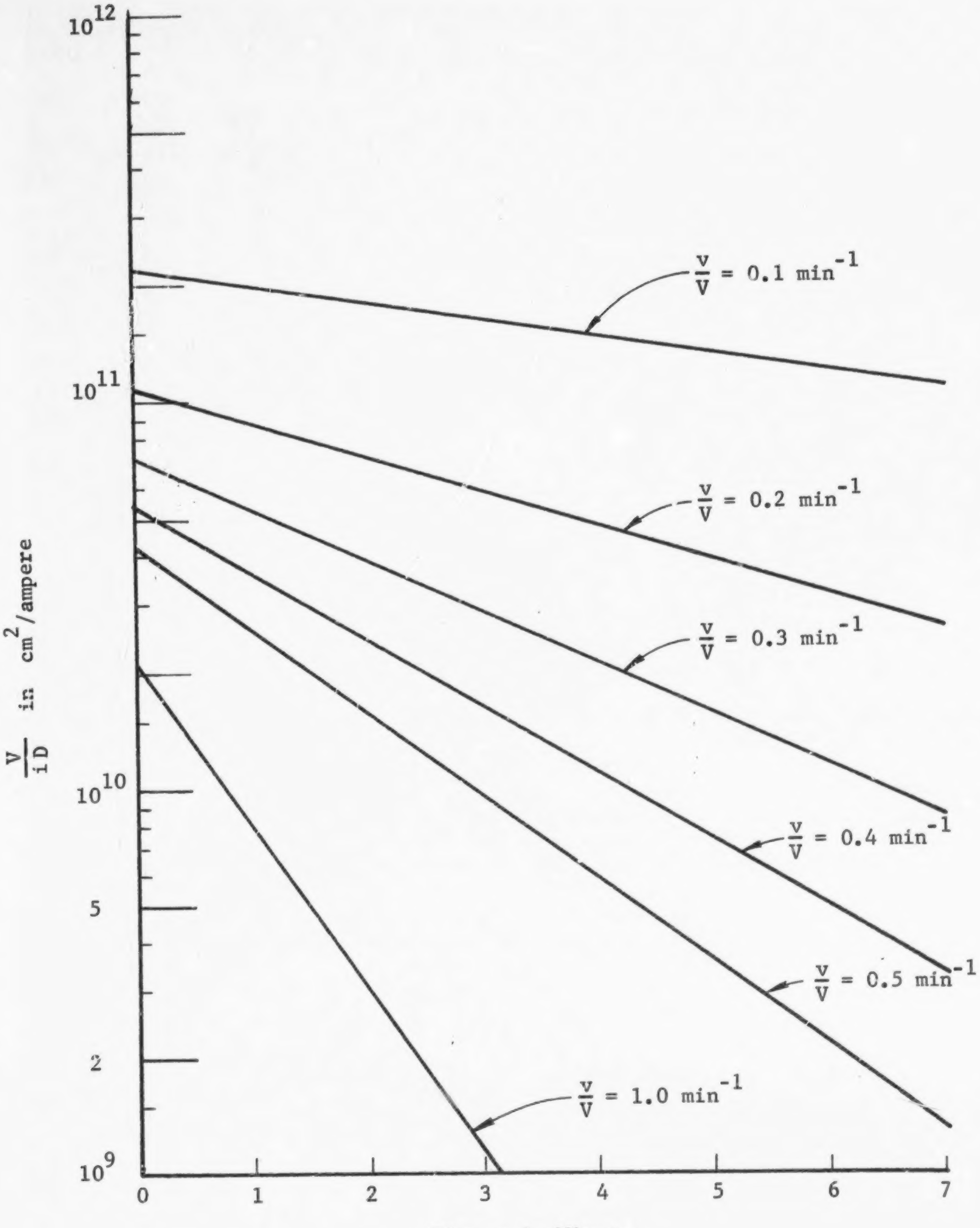

Figure 14. Time Which Must Elapse to allow the Concentration of Ozone to Decrease to 0.1 ppm

## Appendix D

## EFFECT OF PULSED BEAMS ON THE READINGS OF RADIATION DETECTION INSTRUMENTS (29)

A method of calculating the useful limits of instrument readings used in a pulsed beam.

$$N_{avg} = \frac{60N_{ins}PR}{10^6}$$

where

$N_{avg}$ = average count rate (counts/min)
$N_{ins}$ = Instantaneous count rate (counts/sec), i.e. maximum permissible count rate for the instruments in a continuous, steady radiation field.
$P$ = pulse length (microseconds)
$R$ = pulse rate (pulses/sec.)

An example of this calculation is as follows:

$N_{ins}$ = 1670 counts/sec. - maximum capability as quoted by the manufacturer.
$P$ = 5 microseconds
$R$ = 350 pulses/sec

$$\frac{(60)(1670)(5)(360)}{10^6} = 180 \text{ cpm}$$

This example shows that a reading, using this instrument, of more 180 counts/min is subject to error.

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## Appendix E

# RECOMMENDATIONS FOR THE SAFE OPERATION
# OF
# PARTICLE ACCELERATORS

MORP 68-2

# RECOMMENDATIONS for the SAFE OPERATION of PARTICLE ACCELERATORS

by
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FEBRUARY 1968

U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
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# FOREWORD

The trend in particle accelerators is toward smaller machines that produce high-intensity radiation. These accelerators are finding a wide application in activation analysis, physics, radiography, crosslinking of polymers, medical therapy, and isotope production. For many of these machines there is a lack of generally accepted radiation safety procedures. This report is the culmination of a project to develop a set of basic recommendations for the safe operation of particle accelerators.

These recommendations are intended for the use of particle accelerator operators, administrators, and State radiological health personnel. They should be considered as the minimum safety procedures for accelerator facilities, and are intended to supplement existing regulations or standards and to emphasize the more important items in an accelerator radiation safety program.

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# INTRODUCTION

The Radioactive Materials Section has for some time been investigating the radiation hazards associated with particle accelerators. Efforts have been made to: 1) determine the extent of accelerator use in medicine, research, and industry, 2) evaluate the occupational radiation hazards presented by such equipment, and 3) investigate monitoring techniques, survey equipment and dosimetry around such accelerators. This has been accomplished through both "in-house" activities (1-3) and work performed by contractors (4).

These investigations revealed an apparent lack of generally accepted safety procedures for particle accelerator facilities. Thus, in October 1967, a list of interim recommendations for the safe operation of particle accelerators was drafted and distributed within the NCRH for comment. A revised list was then sent to State health departments, other radiological health personnel, and accelerator users for their review. These comments and suggestions were evaluated in January 1968, and where feasible, were incorporated into the list as it now appears. This report has been prepared to disseminate the recommendations rapidly and to provide a basis for further discussion in the continuing evaluation of safety guidelines.

Terms used in the recommendations, such as radiation protection supervisor, qualified expert, and interlocks, have the same definition as those found in National Bureau of Standards (NBS) handbooks and other references. (See Appendix A)

Appendix B summarizes information on previous known accelerator accidents which have been reported in the literature.

# SCOPE

The term "particle accelerator" is very broad and obviously covers many types of devices. It is generally defined as a device used to impart kinetic energy to electrically charged particles such as electrons, protons, deuterons, and helium ions. The recommendations that follow refer to devices that accelerate particles to energies greater than approximately 1 MeV, with the exception that they also apply to neutron generators which operate with a potential of about 150 kV. Such accelerators as cyclotrons, betatrons, linear accelerators, Van de Graaff accelerators, Cockcroft-Walton type neutron generators, and resonant transformers are included.

The recommendations should be considered as the basic or minimum safety procedures for all such accelerator facilities. Amplification of any and all items as they apply to a specific facility is encouraged. The intention here is to supplement existing regulations or standards (5-11) and to emphasize the more important items in an accelerator radiation safety program. Individuals should refer to and be familiar with State and/or federal regulations and standards regarding exposure to ionizing radiation, accelerator shielding, and other applicable radiological health considerations.

## RECOMMENDATIONS FOR THE SAFE OPERATION OF PARTICLE ACCELERATORS

### Administration and Personnel

1. A responsible administrator for the particle accelerator facility shall appoint a radiation protection supervisor and, if appropriate, a radiation safety committee.

2. The accelerator facility shall be under the guidance of the radiation protection supervisor who shall be responsible for advising on radiation safety at the accelerator.

3. The operator of the accelerator shall be responsible for all operations connected with the accelerator, including radiation safety. The radiation protection supervisor shall have the authority to cease operations at the facility because of radiation safety considerations.

4. No individual shall be permitted to act as an operator of an accelerator until such person has: 1) received an acceptable amount of training in radiation safety as approved by the radiation protection supervisor; 2) demonstrated competence to use the accelerator, related equipment, and radiation survey instruments which will be employed; and 3) been approved by the radiation protection supervisor.

5. Written operating and emergency procedures pertaining to radiation safety shall be established for each accelerator facility by a qualified expert, and approved by the radiation protection supervisor.

6. Operators and other appropriate personnel shall be familiar with and be given a copy of the written operating and emergency procedures pertaining to radiation safety. Such procedures should be posted near the accelerator control console.

### Accelerator Controls

7. Particle accelerators shall be secured when not in operation to prevent unauthorized use.

8. Meters and controls on the accelerator control console shall be clearly identified and easily discernible.

### Interlock Systems

9. All entrances into a target room or other high radiation area shall be provided with interlocks.

10. Only a switch on the accelerator control console shall be used to turn the accelerator beam on and off. The safety interlock system shall not be used to turn off the accelerator beam, except in an emergency. If the interlock system does turn off the accelerator, it shall not be possible to resume operation without resetting the accelerator "ON" switch at the control console.

11. All safety interlocks shall not be dependent upon the operation of a single circuit.

12. A scram button or other emergency power cut-off switch shall be located and easily identifiable in all high radiation areas. Such a cut-off switch shall include a manual reset, so that the accelerator cannot be restarted from the accelerator control console without resetting the cut-off switch.

13. Electrical circuit diagrams of the accelerator and the associated interlock systems shall be kept current and on file at each accelerator facility.

Warning Devices

14. All locations designated as high radiation areas, and entrances to such locations shall be equipped with easily observable flashing or rotating red or magenta warning lights that operate automatically when, and only when, radiation is being produced. Lights of a different color shall be used when other visual indicators are required.

15. All safety and warning devices, including interlocks, shall be checked at intervals not to exceed six months to determine that they are functioning properly, and appropriately serviced.

Radiation Monitoring

16. Appropriate portable radiation monitoring equipment shall be available at the accelerator facility, properly maintained and calibrated, and sensitive to those radiations being monitored.

17. An appropriate radiation monitor shall be used within an accelerator target room and other high radiation areas. This may be: 1) an area monitor with an easily observable indicator that warns of radiation levels above a predetermined limit in accessible areas; and/or 2) a personal radiation monitor of the "chirpie" type carried into the room; and/or 3) a portable survey instrument carried into the room.

18. Personal radiation dosimeters that measure the expected radiations and are of sufficient range to be useful under normal and accident conditions shall be worn by all persons designated by the radiation protection supervisor.

## Radiation Protection Survey

19. Before a new installation is placed in routine operation, a radiation protection survey shall be made by a qualified expert.

20. A radiation protection survey shall be performed when changes have been made in shielding, operation, equipment, or occupancy of adjacent areas, and periodically to check for unknown changes and malfunctioning equipment.

21. Records of all radiation protection surveys, inspections, and maintenance performed on the accelerator and related components shall be kept current and on file at each accelerator facility, and periodically reviewed by the radiation protection supervisor.

## DISCUSSION

The following comments, many of which were made by the reviewers of the draft recommendations, will give some additional background into the writing of the recommendations and will indicate the limitations of the list.

While the need for a radiation protection supervisor is clearly apparent, the need for a radiation safety committee at every particle accelerator facility depends upon the actual use of the accelerator. If an accelerator is to be used for a single purpose under the same irradiation conditions and for a limited number of hours per week, a radiation safety committee may not be appropriate. However, if an accelerator receives heavy use under varying conditions by many groups within an organization, a radiation safety committee should be mandatory. Between these two extremes the decision to have a committee must be based upon the professional judgment of the radiation protection supervisor and the management of the facility.

Throughout the recommendations there is no mention of maximum permissible exposures to radiation since it is felt that the reader should be familiar with applicable State or federal regulations on this subject. Similarly, there is no mention of accelerator shielding or target handling, which are beyond the scope and intent of these recommendations.

Consideration should be given to having at least two accelerator operators on duty whenever an accelerator is in operation. The primary operator should be responsible for all operations pertaining to the accelerator and an assistant operator should be available for other duties, such as radiation monitoring with a portable detection instrument, answering telephones, etc.

If for any reason, it is necessary to intentionally bypass a safety interlock or interlocks, such action should be: 1) authorized by the accelerator operator or other responsible person, 2) recorded in a maintenance log or other record and posted at the accelerator control console and 3) terminated as soon as possible.

Similarly, another desirable feature of an interlock system might be individual pullout-type plugs that a person entering the target room must remove from a rack and carry with him at all times while in the target room. It would then be necessary to return all plugs to the rack before the accelerator could be started.

It is suggested that all safety interlocks be "fail safe," i.e., designed so that any defect or component failure in the interlock system prevents operation of the accelerator.

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## DEFINITIONS

**High Radiation Area:** Any area, accessible to personnel in which there exists radiation at such levels that a major portion of the body could receive in any one hour a dose in excess of 100 millirem.(7)

Interlock: A device for precluding access to a high radiation area by automatically reducing the exposure rate upon entry of personnel.(3)

Qualified expert: A person having the knowledge and training to measure ionizing radiation, to evaluate safety techniques, and to advise regarding radiation protection needs. For example, persons certified in this field by the American Board of Radiology, or the American Board of Health Physics, or those having equivalent qualifications.(3)

Radiation Protection Supervisor: Person directly responsible for radiation protection. It is his duty to insure that all procedures are carried out in compliance with pertinent established rules.(1)

NCRP Report No. 33(3) states further that a radiation protection supervisor (who may be the user himself) shall be designated for every installation to advise on the establishment of safe working conditions according to the recommendations of NCRP Report No. 33 and in compliance with all pertinent federal, State, and local regulations. He should be familiar with the basic principles of radiation protection in order to properly discharge his responsibilities, although for details he may consult with appropriate qualified experts.

# SUMMARY OF PUBLISHED ACCELERATOR ACCIDENTS INVOLVING RADIATION EXPOSURE

1. ACCELERATOR TYPE: Medical 1,200 kV Electrostatic Generator
DATE: December 1, 1944
LOCATION: Massachusetts General Hospital, Boston, Mass.
NO. INDIVIDUALS EXPOSED: Six
EXPOSURE: 1000-2000 "tissue roentgens"
PRIMARY CAUSE: Lack of appreciation of hazard
DESCRIPTION OF ACCIDENT:

The target of an electrostatic generator in a large hospital was removed in order to determine the size and location of the focal spot using a piece of film. It was known that there was a definite danger in exposure to the direct beam but it was thought that it would be safe to stand at a distance of several feet. Consequently, six staff members entered the room while the machine was in operation to observe the fluorescence due to the electron beam. Severe radiodermatitis developed over much of the body areas of the exposed individuals.

Ref: Robbins, L., et al.; "Superficial 'Burns' of Skin and Eyes from Scattered Cathode Rays;" Radiology, Vol. 46, No. 1, 1946.

2. ACCELERATOR TYPE: Linear Accelerator
DATE: Not stated
LOCATION: Some university
NO. INDIVIDUALS EXPOSED: Two
EXPOSURE: Not stated
PRIMARY CAUSES: Failure to follow established operating procedures and target area not completely barricaded
DESCRIPTION OF ACCIDENT:

Two research assistants entered the target area of a linear accelerator without notifying the accelerator operator. They also failed to remove an interlock key and ignored warning lights, signs, and the sound of the accelerator klystron pulsers. One worker leaned over, adjusted the target by hand, and when bending over still more to make the alignment by eye, noticed a bluish iridescence in his eyeglasses. Both realized what had happened and left target area immediately. No biological damage was found.

The target area, which was normally barricaded, was made accessible by construction work. However, each researcher was experienced and familiar with proper safety precautions.

Ref: Hayes, Daniel F., A Summary of Accidents and Incidents Involving Radiation in Atomic Energy Activities, June, 1945 through December, 1955. TID 5360 pp. 66 (August, 1956).

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| 3. | ACCELERATOR TYPE: | Linear Accelerator |
| | DATE: | Not stated |
| | LOCATION: | Some university |
| | NO. INDIVIDUALS EXPOSED: | One |
| | EXPOSURE: | Not stated |
| | PRIMARY CAUSES: | Inadequate indoctrination of worker, exposure area not completely barricaded, and unwarranted assumption by accelerator operator that area was clear of workers. |

DESCRIPTION OF ACCIDENT:

A part-time worker, whose job it was to fill vacuum pump traps, ignored warning devices and signs, and climbed across the top of the accelerator shielding into an exposure area. He thus avoided the interlocked gates. The operator, assuming the worker was through with his work, proceeded to warm up the machine and operate it.

The worker was not exposed to the primary beam and no signs of biological damage were found.

Ref: Hayes, Daniel F., A Summary of Accidents and Incidents Involving Radiation in Atomic Energy Activities, June, 1945 through December, 1955. TID 5360, pp. 67 (August, 1956)

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| 4. | ACCELERATOR TYPE: | Electron Linear Accelerator |
| | DATE: | January 6, 1959 |
| | LOCATION: | Livermore, California |
| | NO. INDIVIDUALS EXPOSED: | Seven |
| | EXPOSURE: | 41 rem |
| | PRIMARY CAUSE: | Reliance on incomplete safety interlock circuits |

DESCRIPTION OF ACCIDENT:

A new electron linear accelerator was being operated to accumulate data to enable the engineering section to design permanent equipment for this machine. A number of remote operating circuits were not in operation, including remote controls for the tungsten beam definers, remote radiation monitoring system, and the interlocked barrier to the beam room area. The barrier was temporarily replaced by 4 x 4 ft. plywood and a warning sign.

A series of adjustments were being made on beam defining plates. Radiation surveys were made with negative results when personnel entered the

7. ACCELERATOR TYPE: Cyclotron
DATE: June, 1964
LOCATION: Berkeley, California
NO. INDIVIDUALS EXPOSED: One
EXPOSURE: 3.4 rem whole-body
PRIMARY CAUSE: Not stated
DESCRIPTION OF INCIDENT:

While removing targets cyclotron bombarded from a vacuum chamber in a high level cave, an employee was exposed to radiation.

Ref: A Summary of Industrial Accidents in USAEC Facilities, 1963-1964. TID 5360 (Supplement 5), December, 1965, pp. 30.

8. ACCELERATOR TYPE: Cyclotron
DATE: January 11, 1965
LOCATION: Berkeley, California
NO. INDIVIDUALS EXPOSED: One
EXPOSURE: Estimated quarterly external whole-body exposure 3.6 rems
PRIMARY CAUSE: Not stated
DESCRIPTION OF ACCIDENT:

While an accelerator technician was preparing for an experiment in the area of a cyclotron, he received a whole-body exposure.

Ref: *Nuclear Safety*, Vol. 7, No. 4, Summer 1966, pp. 496.

9. ACCELERATOR TYPE: Linear Accelerator
DATE: February 18, 1965
LOCATION: Rockford, Illinois
NO. INDIVIDUALS EXPOSED: One
EXPOSURE: Interior of body - 0.2 to 5 rad
Right hand - 42,000-240,000 rad
Right foot - 300-29,000 rad
PRIMARY CAUSES: Failure to follow established operating procedures and insufficient barricade of accelerator room
DESCRIPTION OF ACCIDENT:

An industrial worker was accidentally exposed to an electron beam when he walked into a room to place an octagonal mold on a conveyor belt near the output port of an operational accelerator.

The accelerator was mounted so that 10.8 MeV electrons were directed downward after emerging into the air from a vacuum chamber at a height of 75 cm from the floor. The electron beam spread rapidly in its downward course due to its intrinsic angular distribution coupled with multiple scattering in the window and air. At 46 cm above the floor it struck a conveyor belt whose function it was to carry industrial products through the beam. The conveyor system occupied part of the entryway to the accelerator room. In order to accommodate this conveyor system the bottom of the door, guarding the entryway, had been sawed off. The worker gained entrance to the accelerator room through the resulting gap without tripping the electrical interlocks. After the accident, the door was redesigned to accommodate the conveyor system without leaving a gap.

Exposure resulted in double amputation 5-6 months later.

Ref: Lanzl, L. and Rozenfeld, M., "Injury Due to Accidental High-Dose Exposure to 10 MeV Electrons," Health Physics Vol. 13, No. 3 (1967),pp. 241-251.

10. ACCELERATOR TYPE: Van de Graaff
DATE: May 22, 1956
LOCATION: Oak Ridge, Tennessee
NO. INDIVIDUALS EXPOSED: One
EXPOSURE: Estimated hand (finger) exposure 51 rem
PRIMARY CAUSE: Beam shutter failure
DESCRIPTION OF ACCIDENT:

A physicist received an exposure when the beam shutter of a Van de Graaff machine opened inadvertently while he was in target room making adjustments on experimental apparatus.

Ref: Nuclear Safety, Vol. 7, No. 4, pp. 497.

11. ACCELERATOR TYPE: Not stated
DATE: 1966
LOCATION: Not stated
NO. INDIVIDUALS EXPOSED: One
EXPOSURE: 300 rem to one foot
PRIMARY CAUSE: Not stated
DESCRIPTION OF INCIDENT:

A technician was exposed to an estimated 300 rem of X-ray to one foot in an accelerator incident.

Ref: Annual Report to Congress of Atomic Energy Commission for 1966; January 1967, pp. 350.

12. ACCELERATOR TYPE: 3 MeV Van de Graaff
DATE: October 4, 1967
LOCATION: Harmarville, Pennsylvania
NO. INDIVIDUALS EXPOSED: Three
EXPOSURE: Two men 500-600 rem whole body.
Third man 100-200 rem whole body.
Exposure to extremities may be higher.
PRIMARY CAUSE: Not stated (still under investigation)

cell after the first three adjustment runs. No survey was made after the fourth and fifth runs. A survey made after the sixth run showed 1,000 r per hour level.

During all entries to the cell, the key which was designed to lock all controls in the "OFF" position was removed from the control panel.

It was determined that the film badges had been exposed to about 200 keV energy gamma radiation. An exposure dose of 41 r was assigned to physicist A. This dose was received in a period of about one minute, which was the established time he worked alone on plates 3 and 4 and entered the cell to measure very high radiation levels. The next highest reading of 400 mR was received by physicist B. All others received less than 50 mR.

Reliance was placed for safe operation on incomplete safety interlock circuits. Extreme care should be exercised in all situations where it is known that mechanical safety may be incomplete or inoperative.

Ref: A Summary of Industrial Accidents in AEC Facilities, December, 1961. TID 5360 (Suppl. 3-Revised) pp. 8.

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| 5. | ACCELERATOR TYPE: | Van de Graaff |
| | DATE: | November 8, 1960 |
| | LOCATION: | Sandia Corporation, Albuquerque, New Mexico |
| | NO. INDIVIDUALS EXPOSED: | Two |
| | EXPOSURE: | Electron beam - by indirect measurement using film badge: 760 rads incident dose to face of employee "A;" 53 rads total body dose to employee "B" |
| | PRIMARY CAUSE: | Operator failed to check potential radiation source |
| | DESCRIPTION OF ACCIDENT: | |

An employee "A," was accidentally exposed to an electron beam emanating from a Van de Graaff accelerator while setting up an experiment in front of the beam tube.

The machine operator, employee "B," put the machine on self-charge with "A's" consent and knowledge, as "A" entered the beam room. This was done to check the self-charge rate and limit of the machine. The term "self-charge" refers to the operation of the belt which places a static charge on the high voltage terminal. The beam current and belt charge (the normal source of electrons) were not turned on. Therefore, there should have been no detectable emission from the beam tube at this time.

"A" proceeded to end of the beam tube and began setting up his experiment. After approximately two minutes, he came out of the beam room, since his face felt warm. He then went to the washroom and washed his face. "A" asked "B" if there was any residual beam current. The operator stated that the beam current was not on, but that he would check. "B" entered the beam room with a low range survey meter and made a measurement in front of the beam tube. At first he saw no reading, but as he started to leave, the meter pegged at 20 millirems.

"A" received multiple radiation burns in the middle section of the face, abdomen, and both hands. Employee was not wearing his film badge. However, an indirect measurement was made by placing a film badge at the 33 cm distance and exposing it under simulated conditions. Calibration was interpreted as 760 rads incident dose to the face at 33 cm.

"B" received a total body dose of 53 rads as determined by film badge reading.

Ref: (1) Burnett, W. D., Rarrick, H. L. and Tucker, G. E., "Van de Graaff Electron-Beam Exposure at Sandia Corporation" Nuclear Safety, Vol. 4, No. 4, June, 1963, pp. 155.

(2) A Summary of Industrial Accidents in USAEC Facilities, December, 1961. TID 5360 (Supplement 3-Revised), pp. 23.

(3) Bliss, S. P., "Medical Aspects of an Accidental Exposure to Van de Graaff Generator," (In) "Premier Colloque International Sur la Protection Aupres des Grands Accelerateurs," Paris, Presses Universitaires de France, pp. 36-39.

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| 6. | ACCELERATOR TYPE: | Gradient Synchrotron |
| | DATE: | October 17, 1963 |
| | LOCATION: | Argonne, Illinois |
| | NO. INDIVIDUALS EXPOSED: | Two |
| | EXPOSURE: | Whole body exposures of 3.8 rem and 2.8 rem |
| | PRIMARY CAUSE: | Incorrect Beam Stopper |
| | DESCRIPTION OF INCIDENT: | |

Employees exposed while making adjustments on a gradient synchrotron. Before the work of adjusting the synchrotron began, a beam stopper was inserted into the synchrotron to prevent exposure to the employees. However, the correct beam stopper was not inserted and the employees carried out their assignment unaware of this.

Ref: A Summary of Industrial Accidents in USEAC Facilities, 1963-1964. TID 5360 (Supplement 5), December, 1965, pp. 22.

DESCRIPTION OF ACCIDENT:

A Van de Graaff accelerator was being used for activation analysis. The exposure took place apparently as a result of the accelerator not shutting off after the irradiation of a sample of oil. The three men entered the target room, removed the sample, and then attempted to locate the source of trouble with the target cooling system. Possible explanations for the exposure appear to suggest the failure of the safety interlock system to shut off the accelerator and the lack of, or adherence to, proper operating and radiation safety procedures.

> Ref: "Hearings before the Subcommittee on Public Health and Welfare of the Committee on Interstate and Foreign Commerce, House of Representatives, on H.R. 10790," Serial No. 90-11, statements of James G. Terrill, Jr., Director, National Center for Radiological Health, pp. 427, U.S. Government Printing Office.

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Contract PH 86-67-193; William M. Brobeck and Associates; October 1968; MORP 68-12;
RMS, MORP, NCRH, PHS, DHEW.

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